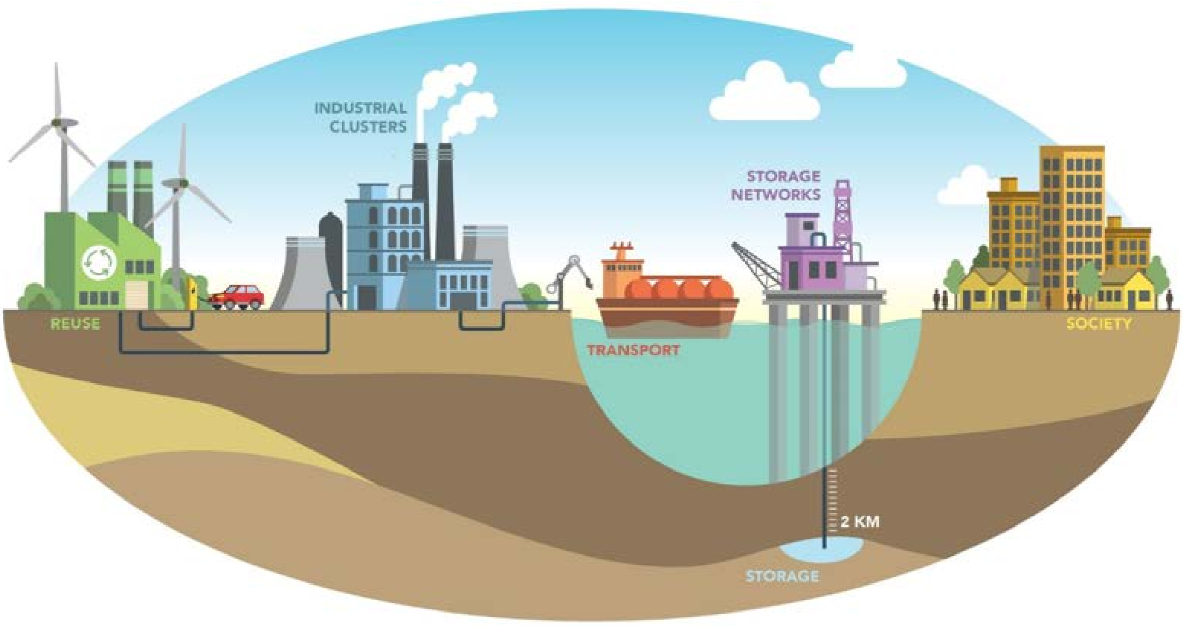
Final Report Public

1. Identification of the project and report

Project title	Accelerating Low Carbon Industrial Growth through CCUS: ALIGN-CCUS
Project website	https://www.alignccus.eu/
Reporting period	01 September 2017 – 30 November 2020

2. Contact for information:

Name	Peter van Os (TNO) Project Coordinator
Email	peter.vanos@tno.nl
Phone number	+31 6 512 999 74



Participanting organisations

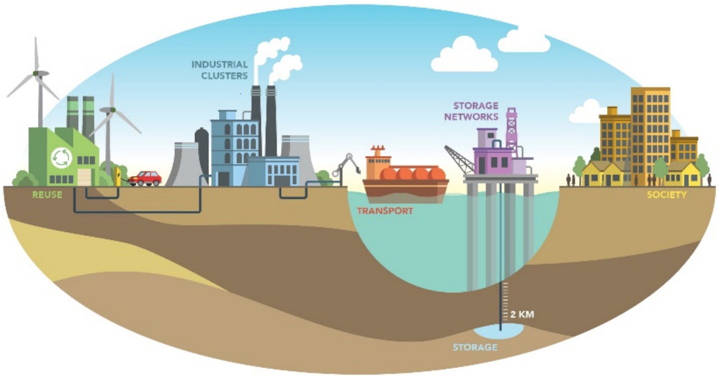
Organisation	Country
TNO	Netherlands
SINTEF IND	Norway
British Geological Survey (UK)	United Kingdom
RWE Power	Germany
University of Leiden (NL)	Netherlands
Asahi Kasei Europe (DE)	Germany
Bellona Europe (NO)	Norway
CO2 club association (RO)	Romania
FEV GmbH (DE)	Germany
Forschungszentrum Jülich (DE)	Germany
GeoEcomar (RO)	Romania
Heriot-Watt University (UK)	United Kingdom
IFE (NO)	Norway
Imperial College (UK)	United Kingdom
Mitsubishi Hitachi Power Systems Europe (DE)	Germany
Norcem AS / Heidelberg Cement (NO)	Norway
Norwegian University of Science and Technology (NO)	Norway
National University of Political Studies and Public Administration (RO)	Romania
PicOil Info Consult (RO)	Romania
Rijksuniversiteit Groningen (NL)	Netherlands
RWTH Aachen University (DE)	Germany
Scottish Enterprise/ Scottish Government (UK)	United Kingdom
TAQA Energy BV (NL)	Netherlands
Technology Centre Mongstad (NO)	Norway
Tees Valley Combined Authority (UK)	United Kingdom
University of Southeast Norway (NO)	Norway
University of Edinburgh / Scottish Carbon Capture & Storage (UK)	United Kingdom
University of Sheffield (UK)	United Kingdom
YARA (NO)	Norway

3. Description of activities and results

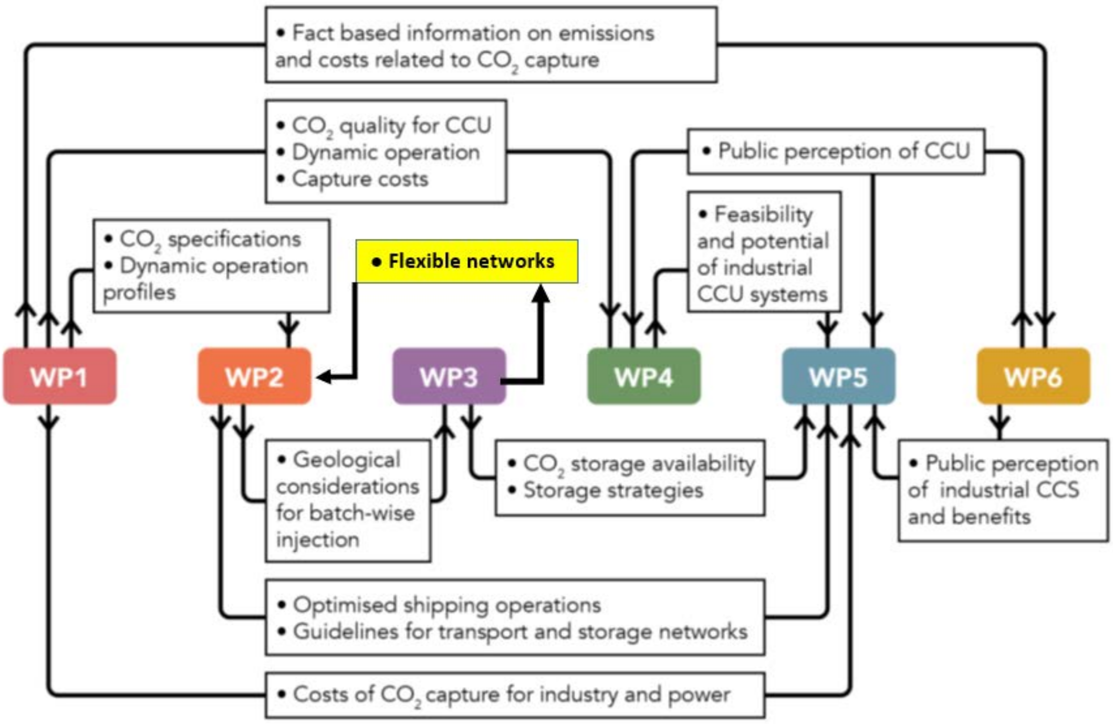
WP0: Project Management and Dissemination

ALIGN-CCUS covers the whole Carbon, Capture, Utilisation and Storage (CCUS). It was one of the first projects where capture, transport, storage, utilisation, clusters and public perception interact to deliver the overall project objective: to accelerate the transition of current industry and power sectors into a future of continued economic activity and low-carbon emissions, in which CCUS plays an essential role. ALIGN-CCUS addressed specific issues across the CCUS chain for industrial regions in ERA-NET ACT countries, enabling large scale, cost effective implementation of CCUS by 2025. All the chain elements contributed to this overall objective.

Dissemination was an important part of ALIGN-CCUS. Dissemination of project results was actively pursued, considering the interest of the project partners. The professional dissemination team was proactive in branding ALIGN-CCUS and making the project known by the public and scientific community.



ALIGN-CCUS Logo and project overview picture



Key interactions between the 6 technical work packages of ALIGN-CCUS

WP1: Enable near-term deployment of integrated capture facilities and cluster development

<u>Objectives</u>
WP1 has been divided into four tasks and the objectives for each of them together with a statement related to successful achievement or not are written in the tables below.

Task 1.1: Solvent emissions

Cost-efficient control of emissions to environmentally acceptable standards and reduced solvent losses.	Environmentally acceptable standards for emission of amines and amine degradation products are still not existing, but we have looked into amine and ammonia emissions, which are the most relevant. Furthermore, we have looked into efficient online measurement of nitrosamine emission and the cost-efficiency is evidenced in the reports D1.1.7 and D1.4.3.
Thorough understanding of aerosol growth and countermeasures.	While there are still some gaps, we believe this has been achieved. NTNU's model gives reasonable prediction of aerosol-based emissions, meaning the mechanisms of growth are well described. The countermeasures are well described.
Demonstration and validation of countermeasures at TRL 6/7.	Here, we also have some gaps. The tests performed at RWE were too short to have conclusive, irrefutable proof of the efficiency. But the demonstrations and validation of reduction in emissions and number of particles were achieved.
Verify the effect of dynamics on solvent emissions and the possible adaption of countermeasures.	This is done and it is shown that no adaptation of countermeasures is needed.

Task 1.2: Solvent management

Maintain optimal solvent quality for long-term operation, leading to a solvent consumption of less than 0.3 kg amine per tonne of CO_2 captured	For both tested solvents unique long-term operation >12,000 h was demonstrated. Without any countermeasures, the solvent consumption is slightly higher (0.45 kg for CESAR1 and around 0.4 kg for MEA), but with efficient emission and degradation countermeasures it is demonstrated that these numbers can be reduced without drastically increasing the capture costs.
Interconnecting flue gas quality, unit operation and operational conditions to chemistry of solvent degradation	Long-term testing at the RWE plant as well as testing at PACT, TCM and at the Tiller facility has clearly shown some relationship between operating conditions and the effect on degradation. See the conclusions in the following result section for Task 1.2 in WP1.
Demonstrate advanced solvent monitoring tool	It is shown that online monitoring tools like Raman spectroscopy and UV-vis can provide valuable data for the analysis of important parameters that drive corrosion and degradation and can be used as an alarm that countermeasures are necessary, but need further development for commercial application".

Task 1.3: Process dynamics- and control

Demonstrate reliable and efficient control structures for flexible and cost-efficient operation of capture plants.	A control system based on Non-Linear-Predictive Control has been tested for the CESAR1 solvent system at the Tiller CO_2 Lab and shown to be efficient in terms of both flexible and cost-efficient operation. More specifically it was possible to achieve almost 100% capture without any significant increase in SRD.
Demonstrate a 5-8% reduction of the energy requirement compared to simple control systems for a flexible power plant.	In the ALIGN-CCUS project, this comparison was actually not conducted for the CESAR1 solvents system, but it has been demonstrated in a previous project[1] that this is achievable for MEA. It was experienced however, in the ALIGN-CCUS project that the CESAR1 solvent system responded more quicker and as such it is believed that at least this potential energy reduction is achievable for CESAR1 as well.
Establish emission control strategies, which keep the emission below legal permit for certain flexible operational scenarios.	In ALIGN-CCUS, emission control strategies have mostly been related to physical means of emission countermeasures, like water-wash and Brownian Demister Unit (see Task 1.1) and not so much on the process control system in that respect. However, a prerequisite for using an advanced control system like NMPC is an adequate model of the emission mechanisms, online emission monitors with relevant response for the

[1] Kvamsdal, H.M., Hauger, S. O., Gjertsen, F., Enaasen Flø, Colombo, K.E., Mejdell, T., and Hillestad, M., Demonstration of two-level nonlinear model predictive control of CO_2 capture plants, presented at the GHGT-14 conference in Melbourne, Australia, 2018

	control system and relevant manipulate variables. The work done in ALIGN-CCUS will serve as a basis for further studies into this option.

Task 1.4: Benchmarking and cost drivers

Establish a new cost-efficient benchmark capture process and establish guidelines for optimal design of integrated CO_2 capture plants with 1st and 2nd generation technologies.	The first part of this objective is based on previous work and is also published by others. However, in ALIGN-CCUS, a more comprehensive study has been done which includes 3 different use cases. The results show that it is not so evident that the CESAR1 solvent system is less costly than MEA for either of the cases, but it is also seen that the cost of the solvent is one of the major contributions to the capture cost. Though both the price of the solvent system and the loss of the solvent was a focus within the project, this should be further explored. Related to the second part of this objective, this has been investigated and optimization of solvent management systems and efficient emission countermeasures needs more attention.
Scale-up novel emission countermeasures and estimate costs of preventing emissions for full-scale application in the power and industry sectors.	In order to compare the two solvent systems, the cost for large-scale implementation is determined, which also has included some options for emission countermeasures. The latter included "dry-bed" and turbulent pre-treatment for the power-plant case, a "Brownian demister unit" for the WtE case, and a double water-wash for the cement case.
Optimize the design of post-combustion technology showing cost optimization options and highlighting potential cost reductions.	Optimal integration of the capture plant for all three use cases has been explored and potential cost reductions are identified. It is interesting to notice the importance of the cost of the solvent while the investigated emission countermeasures did not influence that much on the cost of CO_2 capture. Thus, reducing solvent losses is important for potential cost reductions.

<u>Main results</u>

The results shown in the following for each task in WP1 are as summarized in the public guideline reports, i.e., D1.1.7, D1.2.6, D1.3.5, and D1.4.3, respectively.

Task 1.1: Solvent emissions

Within the ALIGN-CCUS project, technologies for emission control were reviewed, tested at lab and pilot scales, and evaluated from both technical and economic perspectives. These guidelines are a compilation of the project findings. The main message that these guidelines hope to convey is that emission control is technically feasible (for mitigating both aerosol and volatile emissions) and does not lead to prohibitive costs.

The results are summarized in the table on the next page. The "information basis" criterion reflects the level of data access that we had for performing the evaluations. Naturally, for technologies tested within the ALIGN-CCUS project, the information basis is good. While all technologies assessed are at high technology readiness level (TRL 6-9), the emission removal efficiency for some of these technologies remains more uncertain. The last criteria are OPEX and Bare Equipment Costs (BEC) of the additional equipment needed for installing these countermeasures.

The units of the cost criteria are chosen to facilitate the calculations of OPEX and BEC at different scales, as showed next. As an example, we show the OPEX and BEC determination for a water wash (WW) unit in a plant treating 1 million normal cubic meters of gas per hour (Nm^3/hr):

$$OPEX_{ww} = 0.078\ \frac{€}{1000\ m^3} * 1\ 000\ 000 \frac{m^3}{h} = 78\,€/h$$

$$BEC_{ww} = 11.7\ \frac{1000\ €}{m^3/s} * 1\ 000\ 000 \frac{m^3}{h} * \frac{h}{3600\ s} = 3.25\ M€$$

The unit cost in blue are taken from the table and can be easily converted into useful OPEX and BEC values for a given scale. For this report, it was decided not to calculate CAPEX from the BEC, as the financial criteria to do so will vary from project to project.

The impact of emission control on the cost of CO_2 capture (i.e., in terms of €/tonCO_2) is discussed in another public document (D1.4.3), in which different use cases are evaluated with varying CO_2 concentrations. Within the current guidelines, we focus on the techno-economic evaluation of the stand-alone technologies. This should provide the means to compare alternative technologies, and decide on a preferred technology combination (i.e., an emission control strategy) for a specific plant.

Overview of technology assessments[1]

Technology	Information basis	Scale tested	TRL	Removal efficiency	OPEX (€ / 1000 m^3)	BEC (k€ / m^3/s)
Water wash		Pilot	9		0.0780	11.7
Acid wash		Pilot	7		0.0420	7.6
Wet electrostatic precipitator		Pilot, lab	6		0.1200	24.0
Brownian demister unit		-	7		0.0900	10.7
Gas-gas heater		-	6		0.1000	10.0
Turbulent pre-treatment		Pilot	6		0.0830	3.6
Upstream base addition		-	6		0.0003	0.5
Lean solvent temperature		-	6		0.0009	0.0
Dry-bed		Pilot	6		0.0090	5.2

The most important results regarding the reduction of the risk for the implementation of commercial capture plants and to accelerate the implementation of CCUS are:

- In general, volatile emissions can be well controlled by installing water- and acid washes. The dry bed may be an interesting addition, as it has the potential of lowering the OPEX of the acid wash.
- Options to control aerosol-based emissions include Brownian demister units (BDU), the turbulent pre-treatment (TPT) and the dry bed. Of these, there is more clarity on the efficiency of removal achieved with the BDU. For the TPT, and the dry bed, additional investigations are suggested.
- The wet electrostatic precipitator (WESP) is not recommended as a technology for mitigating aerosol-based emissions. The OPEX and BEC are higher than that of a BDU. But most importantly, there is no evidence that a WESP can control emissions; on the contrary, and depending on the operational conditions, the WESP could even lead to increased aerosol emissions.

Task 1.2: Solvent management

Degradation of the solvent and corrosivity are decisive factors for the CO_2 capture costs. The right choice of degradation countermeasures allows the operator of the capture plant to minimize solvent consumption and operational issues like foaming and fouling, downtimes for maintenance and waste streams and offers the supplier the chance to use cost effective materials for the design of the capture plant.

The most important results achieved in ALIGN-CCUS regarding the risk reduction for the implementation of commercial capture plants and to accelerate the implementation of CCUS are:

- For both solvents low specific solvent consumptions were determined in comparison with published results from other capture plants.
- CESAR1 degrades much slower than MEA and has a lower specific reboiler duty. On the other hand, CESAR1 has higher emissions and is more expensive to purchase (€/kg amines).

- "Bleed and Feed" as solvent management strategy would require a full replacement of the solvent holdup and careful cleaning of the capture plant to be effective.
- Reclaiming by ion exchange seems to be a more promising management strategy, but a careful analysis of the waste streams must be carried out and further investigation is needed.
- If threshold values for individual contaminants that might act as catalyst for solvent degradation exist, they seem to be so low that it is questionable if it is possible to remain below this threshold in practical applications.

The most important results regarding the further development of the theory, investigation methodologies and models on solvent degradation and ways to optimize solvent management technologies achieved in ALIGN-CCUS are:

- Online monitoring tools like Raman spectroscopy and UV-vis can provide valuable data for the analysis of important parameters that drive corrosion and degradation and can be used as an alarm that countermeasures are necessary but need further development for commercial application.
- NO_2 could be an important trigger for degradation. Investigations about its role in amine degradation are part of the follow up project of ALIGN-CCUS, LAUNCH (ACT2).
- Oxygen removal from the solvent has shown its potential. Tests at higher TRL will have to demonstrate its effectiveness and robustness. This system could also prevent degradation caused by oxygen fed in via utility flows like make up water.

Task 1.3: Process dynamics and control

Due to the penetration of renewable intermittent energy in most energy systems, natural gas and coal power plants must be operated in a flexible mode to stabilize the electrical grid. In such a regime of dynamic and flexible operated power plants, the flue gas treated in the capture plant will have to change accordingly, and the capture plants will need to adapt these changes as smoothly as possible. The present task dealt with optimal control of the capture plant in general, but especially under a regime of flexible part load power plants.

The plant control system has been based on Non-linear Model Predictive Control (NMPC) where a dynamic model of the plant runs in parallel with the plant. The algorithm sets the setpoint of lean liquid flow and the reboiler duty based on an objective function that minimizes energy and keeps the setpoint of the capture rate. The NMPC system is integrated with the basic control system at Tiller.

The tests with the NMPC showed:

- A smooth transfer from one capture rate to another could be obtained, from 85% up to 99% capture rate. This facilitates the possibility of using a dynamic real time optimizer that can minimize the capture cost over a longer horizon e.g., to optimize the operation during one day with cyclic variations in the electricity price.
- Changes in flue gas flow rates due to changes in the electric output from the power plant could be controlled well. The NMPC uses the planned change rate in the flue gas in its predictions for future control steps.
- The pilot plant could handle changes in flue gas flow from 130 to 340 m^3/h without operational challenges. This shows that a PCC plant can be very flexible also for part load power plants.
- The NMPC managed also pure disturbances like changes in CO_2 concentration well.
- A "stripper stop scenario" was also tested where the steam to the reboiler was temporarily stopped e.g., to stabilize the grid frequency. However, the present version of the NMPC needs to implement better control of lean loading to avoid unstable conditions.
- The dynamic process model of the plant was well suited for control purposes.

Task 1.4: Benchmarking and cost drivers

One of the aims of the ALIGN-CCUS project is to evaluate if the second generation solvent CESAR1 can be established as the new state-of-the art benchmark solvent system, replacing monoethanolamine

(MEA), and propose an optimal CO_2 capture process implementation and integration with power plants and other industrial sources. The work conducted in ALIGN-CCUS has explored cost reduction options and compared them to the state-of-the art technology following from cost estimates for advanced amine technology. We have investigated the costs of CO_2 capture for three use cases: power, waste-to-energy, and cement plants. For each use case, the CO_2 capture process was proposed and simulated using both the MEA and CESAR1 solvents, and different scenarios were also considered for each case.

Use cases and scenarios investigated within ALIGN-CCUS

Use case	Capacity (reference plant)	Scenarios
Lignite-fired power plant	1000 MW_e (generic plant)	MEA (90% capture rate) and CESAR1 (90, 95 and 98% capture rate). Sensitivity analysis: CESAR1 solvent price.
Waste-to-energy plant	200 ktonne of waste per year (generic plant, combined heat and power)	MEA and CESAR1 (90% capture rate). Sensitivity analysis: CESAR1 solvent price, heat and electricity costs.
Cement plant	1265 tonne of cement per year (based on Norcem's Brevik plant)	MEA and CESAR1 (90% capture rate). For CESAR1, the steam generation is considered using a natural-gas fired boiler, a biomass-fired boiler and heat pump. Two variants of the absorber height are considered. Sensitivity analysis: Cost parameter variations for all scenarios.

Details can be found in the Public Deliverable D1.4.3 but for all cases the difference between the two solvent systems is not large.

We also evaluated the impact of adding emission management technologies to the plants. In general, it is concluded that emission mitigation technologies do not seem to represent a major cost item for CO_2 capture plants. Depending on the solvent costs and emission level considered, they can even lower the cost of CO_2 capture. Also important to notice, emission mitigation technologies will lower the environmental impact of CO_2 capture, and may be necessary, particularly in cases in which the total nitrogen emissions (amines, ammonia, NOx, etc.) are strictly regulated. A more comprehensive review of these technologies and the cost methodology is detailed in the public available report D1.1.7: Guidelines for emission control.

As solvents costs emerge from this work as being one of the main – if not the decisive – criteria for choosing a technology, knowledge gaps and further opportunities for lowering CO_2 capture costs are made evident. The opportunity to lower the costs by focusing on decreasing solvent losses has been remarkably overlooked. Within ALIGN-CCUS, we have taken initial steps in correcting this. While the costs of some emission mitigation technologies are explored within D1.4.3, only solvent replacement is considered as a solvent management strategy. Future work should focus on evaluating the costs of integrating solvent thermal reclaiming (state-of-the-art), and other technologies (under development) to mitigate solvent degradation to CO_2 capture plants. Any decrease in solvent losses (due to controlled emissions and/or degradation) will also lead to a decrease in the environmental impact of the CO_2 capture process and should therefore be considered also from this perspective.

WP2: Removing technical barriers to large-scale CO_2 transport

The three overall objectives of WP2 were:

- Develop optimum handling strategies of both low- and medium-pressure CO_2 on vessels in a transportation network, and in offshore offloading systems including required equipment types.
- Investigate use of different solutions including Floating Production, Storage and Offloading units (FPSOs) and/or subsea solutions and identify new chain configurations.
- Suggest optimum combinations between transport solutions and offshore offloading solutions, and establish a benchmark for alternative transport strategies, including cost considerations.

Task 2.1: Technological challenges of CO_2 shipping and offshore offloading

Task 2.1 has been coordinated by SINTEF with contributions from Imperial College of London (ICL). Input from WP1 on CO_2 capture, as well as WP3 on Storage of CO_2 has been important. Furthermore, there has been communication with WP5 on Clusters. The main objectives of subtask 2.1 were to develop optimum handling conditions and strategies for CO_2 on vessels in a transport network as well as in offshore offloading systems.

Both low and medium pressure conditions were investigated. At medium pressure, liquid CO_2 is transported in tanks on vessels at -28 °C and 15 bar, while low pressure condition typically is at -50 °C and 7 bar. Medium pressure conditions represent proven technology and is used for commercial CO_2 transport, and is also for instance preferred by the Northern Lights project. The study has also focussed on offloading challenges before offshore storage of CO_2. Transportation strategy influences treatment of CO_2 before transport as well as on conditioning before injection, which are important cost considerations for the design of the transport and storage network.

A shipping cost optimisation model has been developed. The model has been used to assess three configurations for CO_2 transport by ship for the two different design pressures (7 bar, 15 bar) for the Norwegian value chain studied in ALIGN-CCUS. Each configuration reflects a different transport option for CO_2 injection into the Aurora formation offshore Norway. Configuration no. 1 allows injection from an onshore hub located at Kollsnes at the West coast of Norway via an offshore pipeline (with transport by ship to the hub). Configuration no. 2 considers injection directly from ships through a buoy system, while configuration no. 3 allows injection from a floating production, storage and offloading vessel (FPSO).

Results show that low pressure implies slightly lower cost than medium pressure for all configurations. Medium pressure has higher transport and intermediate storage cost, more that outweighing somewhat lower conditioning costs. The least cost option is direct injection from the ship, followed by injection from an offshore pipeline coming from Kollsnes. Injection from FPSO has the highest cost. The FPSO design in this study (Panamax) is not compatible with the relatively modest CO_2 supply assumed, resulting in higher costs. Smaller FPSO options could result in lower costs. Further detailed design studies are recommended.

Task 2.2: Safe and efficient injection conditions for batch-wise injection of CO_2

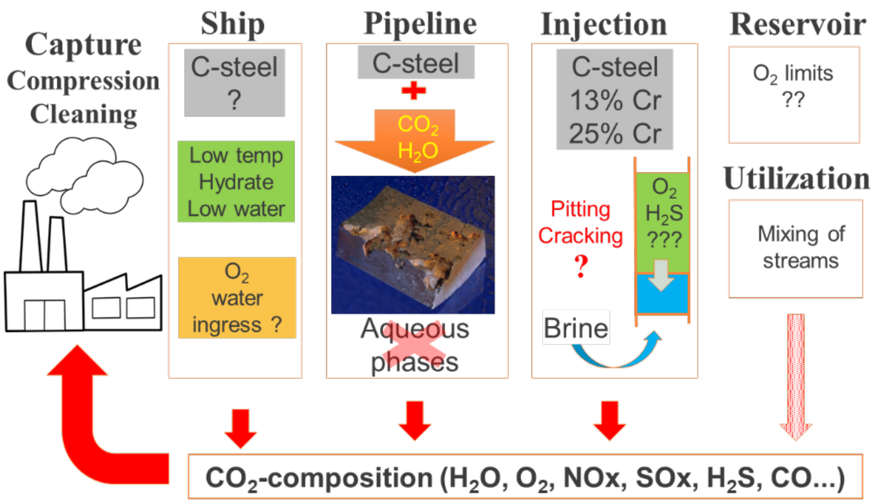
This task was coordinated by TNO. The task has cooperated extensively with WP3 on CO_2 Storage. The main objectives of subtask 2.2 were to document effects of batch-wise and cyclic injection on the integrity of the storage formation in the near-well area and to give recommendations for maximum fluctuation of CO_2 injection pressure and temperature. There has been close cooperation with WP3 on CO_2 storage.

Work in this task was directed along two main avenues; Review effects of fast injection of cold CO_2 on the well materials and potential integrity issues, as well as developing key performance indicators required to develop a monitoring plan for injection.

Ships will supply CO_2 to an offshore injection site in batches, as opposed to pipelines which give a continuous supply of CO_2. Furthermore, the low temperatures of the CO_2 when delivered by ship poses challenges to materials and well integrity. Well integrity is real risk that needs to be understood. In this task we modelled the impacts of batch-wise injection and technically feasible injection conditions were identified which would prevent the integrity of the storage complex from being impeded. The studies focused on impacts of low temperature at high pressures, injection of CO_2 in batches and the integrity of the storage site near the injection well during batch-wise injection. The following possible effects were identified:
- salt precipitation;
- hydraulic fracturing of cap rock;
- thermal contraction of well materials that may lead to formation of leakage pathways up well.

Task 2.3: Variation in CO_2 composition – defining safe operation windows
Institute for Energy Technology (IFE) in Norway was responsible for task 2.3. The task cooperated with WP1 on Capture and WP3 on Storage of CO_2. The main objectives of subtask 2.3 were to validate CO_2 specifications developed in several previous and ongoing projects (like the Northern Lights project) and to see how mixing of CO_2 streams can be performed to avoid unmanageable corrosion and therefore can be safely transported and injected.

The CO_2 coming from a capture plant contains some impurities. Even though concentrations are at the ppm level, these impurities may still under certain circumstances accumulate in the CO_2 handling system. Typical impurities include oxygen, water, NO_2 and SO_x. Several specifications for tolerable levels of impurities in CO_2 have been suggested. The ISO transport standard from 2016 gives no clear recommendation on CO_2 composition due to lack of data, and instead states that the most up to date research should be consulted during pipeline design.



CO2 composition

Since the maximum concentration of a single impurity not giving chemical reactions will depend on the concentration of the other impurities and the temperature, it is not possible to give universal recommendations for what is a safe CO_2 stream composition. The acceptable CO_2 composition will therefore be project specific. However, the presence of NO_2, and the combination of NO_2, SO_2 and O_2 seem to make the CO_2 stream more vulnerable for formation for corrosive phases. A model is needed to establish safe, but not over-strict CO_2 specifications.

An important conclusion from this part of the work is that it is the capture end of the CO_2 chain that should deliver a CO_2 quality which is acceptable to transport and storage.

Task 2.4: Flexible transport and storage networks.
This task has been coordinated by ICL. The task has cooperated closely with WP5, and within WP2, this task and task 2.1 have worked in close contact. Operational flexibility and the ability to employ different capture transport and storage options in the CCUS value chain have substantial benefits for the development of commercial CCUS networks. Such flexibility may involve choices over CO_2 capture rate variations, different modes of CO_2 transport via pipelines, ships or even lorries; different CO_2 transport network design options and choices regarding the geological storage sites / EOR opportunities that may be used as part of the network. The main objective of task 2.4 has been to develop an investment decision framework to enable the appraisal of such options and related uncertainties and engineering flexibilities, so these are factored into investment decisions.

The real options decision framework developed is an extension of the standard financial appraisal methods. It introduces the ability to explicitly quantify the effect of individual sources of uncertainty in each capture, transport and storage option considered. It also accounts for the flexibility that managers need over the timing of their investment when faced with uncertain future cash flows. The model developed considers pipeline transport infrastructure to enable and maximise flexibility for expansion for future large-scale networks, can identify means to combine ship, pipeline and even lorries transport to make use of their respective advantages. The model also can accommodate the intermittency in CO_2 supply during the build-up period of CO_2 capture and therefore also ease integration of small sources of CO_2 within the transport and storage system. Furthermore, the model allows to identify the critical technical features of a transport and storage network to support flexibility and the key economic conditions that these may rely upon. This modelling tool is useful for techno-economic portfolio assessment and optimisation of CCS networks over different planning horizons.

WP2 overall summary of results
Work Package 2 on CO_2 transport is a natural link in the value chain between capture at one end and storage of CO_2 at the other end CO_2 transport consists of preparation for transport (conditioning, liquefaction), ship or pipeline, eventually a hub onshore where CO_2 is offloaded and temporarily stored and then pumped through a pipeline to an injection site (offshore). The work package has had a special focus on transport by ships, although including also pipelines when necessary, such as regarding network modelling.

WP2 has demonstrated that low pressure ship transport of CO_2 may be just as (or even more) attractive than the medium pressure transport option, which is the proven technology today. Cost-wise these two options are quite similar. The cheapest injection option seems to be direct injection from a ship. When injecting, the low temperature in combination with the relatively high pressure poses challenges to materials and the integrity of the well. This is a potential risk, which must be contained at the receiving end of the chain. Another risk factor is presence of impurities in the CO_2 stream. Impurities, even in low concentrations, may cause corrosion. Most preferably this risk should be contained at the CO_2 delivery end (capture end) of the value chain. The work in WP2 has extensively relied on techno-economic assessments and this is also an integral part of the model that has been developed for CCS portfolio assessment and network optimisation.

WP3: Large-scale storage networks

WP3 objectives were to investigate:

- A methodology to produce standardised definitions of the levels of storage readiness for putative storage sites across the North Sea and corresponding activities for them to become a contingent storage resource (Task 3.1);
- A portfolio of selected storage sites that have been characterised sufficiently to provide strategic storage for the leading ALIGN-CCUS industrial clusters most likely to form the backbone of CCUS in north-west Europe (Task 3.2);
- An audit of North Sea transport and injection infrastructure that provides least-cost options for storage network development. (Task 3.3).

All WP3 deliverables and objectives have been successfully achieved incorporating additional linkages and exchanges between the tasks, with WP5, parallel investigations for industry and the ACT ELEGANCY and Acorn projects. The additional exchanges and interactions, which greatly improved the scientific quality of the deliverables were accommodated by adjustments in timing and extension of completion of deliverables. For example: The Netherlands storage site characterisation was extended to include results from the industry Porthos consortium; completion of the infrastructure re-use methodology was extended to enable testing and revision by application to national infrastructure.

Task 3.1: Steps to 'contingent resource' level storage capacity for ALIGN-CCUS clusters
The storage readiness methodology and its application to North Sea sites was completed as planned. A framework of Storage Readiness Levels (SRLs) was presented based on the practise and experience of CO_2 storage site appraisal, regulatory permitting and CCS project planning in the UK, Norway and The Netherlands. Application of the framework communicates what has been achieved and what remains to be completed before a site can become operational. The draft schema was revised by very helpful feedback received during an in-person workshop with industry and regulators. The draft framework was presented at the GHGT-14 conference in Melbourne and improved by additional in-person industry perspective from Shell. The finalised Storage Readiness Levels framework was applied to inform selection of sites for ALIGN-CCUS strategic site selection and characterisation (Task 3.2). Application of the standardised framework to prospective sites in the three countries enabled comparison of sites at benchmark levels and the ranges of expenditure and duration of appraisal over three decades. Sites at 'contingent storage resource' level have been identified in all three of the ALIGN-CCUS North Sea nations.

Application of the SRLs framework informed site selection (Task 3.2) and, in turn, assessment of infrastructure of re-use (Task 3.3) by ALIGN-CCUS research. The framework has been designed to be consistent with and extends the industry commercial development classification, with the addition of four readiness levels spanning the earliest stages of strategic appraisal. The framework is also to be applied to prospective sites in the European CO_2 storage atlas, to integrate regions of northern and southern Europe.

Task 3.2 Sites characterised for strategic storage for the ALIGN-CCUS industrial clusters
'Next sites' were selected and investigated for four North Sea industrial CCUS clusters, each beyond current industry plans for CCUS, sufficient for annual storage of tens of million tonnes CO_2. Research activities were tailored to be specific to national needs.

Selection of storage sites for the UK Teesside and Grangemouth clusters was informed by CO_2 supply profiles (Task 5.1) plotted from industry plans, in collaboration with the ELEGANCY and Acorn projects. Sufficient capacity, injectivity, SRL and availability were included in the selection criteria, also the results of batch-wise injection modelling for Teesside by ALIGN-CCUS (Task 2.2). Options were proposed to achieve storage at annual rates of tens of million tonnes by 2030 for both clusters. Selection of storage sites for the Norwegian Grenland cluster, beyond the plans for the full-scale Northern Lights industry project, was informed by a timeline of CO_2 supply from Scandinavian and northern European sources. Three saline aquifer sites in the Horda Platform area were modelled and injection simulated and potential capacity of the Troll Field once depleted, were assessed for storage capacity of tens to thousands million tonnes CO_2. Strategic assessment of depleting gas fields, stepping out from the permitted P18-4 site, informed the mapping of alternative networks for transport and storage of CO_2 from Rotterdam and Amsterdam, The Netherlands. Simultaneous operation of multiple field sites will be required to meet emissions reduction of the Netherlands Climate Agreement. Total investment and operational costs are calculated and uncertainties assessed for CO_2 compression, transport and storage at rates of 5 and 10 million tonnes per year. Timing is identified as a key factor for availability of depleted fields, also a need for rigorous assessment of integrity and specification for re-use of infrastructure for CCS.

Task 3.3: North Sea transport and injection infrastructure for CO_2 storage network development
The objectives of the transport and infrastructure development research were to: develop criteria for the evaluations of re-usability of offshore infrastructure; identify oil and gas infrastructure suitable for re-use for each ALIGN-CCUS cluster and provide an overview of current legal situation and recommend amendments to legal regimes governing decommissioning of re-usable offshore assets. The objectives were addressed by developing a methodology to map possibilities of re-use from available technical information. The methodology was applied to available technical infrastructure information for the ALIGN-CCUS UK, The Netherlands and Norwegian storage options. Legal considerations for re-use within international, European and national law (UK, The Netherlands, and Norway) were reviewed, recommendations drafted and discussed with invited stakeholders at three national workshops.

Technical criteria for re-use of offshore oil and gas infrastructure to accelerate deployment and reduce the cost of CCS, either published or made available to WP3 ALIGN, were reviewed. The criteria, defined to assess depleting fields and re-use of a field for CO_2 storage, were considered for infrastructure re-use by a CCS project within a reasonable distance. The criteria were ranked, following analysis and application to infrastructure in the vicinity of the ALIGN-CCUS storage options, and presented as an order of application of technical criteria. Experience of applying the criteria in Norway, the UK and the Netherlands highlights the location of infrastructure relative to sites of known and sufficient CO_2 storage capacity is essential when screening for re-use. The availability and lifespan can only be accurately estimated with data from operators, although first estimates can be made with publicly available information. If the three first criteria are met the remaining criteria, requiring detailed information from infrastructure operators, can then be evaluated.

A strategic approach for selection of UK infrastructure for re-use is recommended, from the application of the ranked criteria to UK infrastructure in the vicinity of saline aquifer storage sites investigated by ALIGN. The strategy should include collation and provision of data from operators which is currently difficult to access. The temporal gap between cessation of hydrocarbon production and CO_2 storage should be managed, to maintain facilities and enable re-use of UK infrastructure. Detailed studies of integrity are recommended for infrastructure identified as suitable and of potentially strategic importance as part of a future national network asset for CO_2 transport and storage. An appraisal of infrastructure for re-use should be undertaken early in the planning phase of decommissioning. This is imperative to avoid additional costs and potential weakening of integrity associated with mothballing of infrastructure. Application of the published criteria, in the order of ranking, was used to assess re-use options for potential saline aquifer storage sites in the Horda Platform area, Norway. The short-list of suitable infrastructure in the area was screened by the next criterion, availability in time, ruling out all the identified infrastructure components. Hydrocarbon fields using the infrastructure will be in production until after 2040. New installations will be necessary, at least for the initial development of a CO_2 storage hub in Horda Platform area. Assessment for re-use of depleted hydrocarbon field infrastructure in The Netherlands supported a published conclusion that suitability is dependent on specific requirements of the CCS project. However, in the cases studied, pipeline and platform infrastructure are most regularly suitable for re-use. Simulation of offshore pipelines and wells for CO_2 transport and storage in low-pressure depleted gas fields provide insights into the minimum and maximum injection rates required to maintain a safe operational temperature window. Minimum injection rates, a consequence of the low reservoir pressures in a depleted gas field, can be relatively high for low temperature injection of CO2 in liquid phase at the start of CO2 injection. Over time, as injection continues and the reservoir pressure increases, the required minimum injection rate will decrease.

The most important legal questions related to reusing existing hydrocarbon infrastructure are created by the decommissioning (abandonment and removal) regime for offshore hydrocarbon installations and the way in which reuse impacts the regulation of permanent CO_2 storage activities. The CCS industry in Europe has currently barely any demand for offshore infrastructure, however, the demand from the CCS industry for CO_2 storage is currently increasing and reuse of existing infrastructure will become relevant. Three scenarios are identified for reuse: award of a storage licence during hydrocarbons production; award of a storage licence directly after production ceases and/or a production licence lapses; CO_2 storage to take place several years after hydrocarbons production has ceased. Bridging of the temporal gap, in the third scenario, may be achieved by appointment of either an interim entity or an ‘operator of last resort’ to maintain infrastructure until needed. The main advantage of this solution is that it provides for a tailored solution for this specific situation. The disadvantage is nonetheless that a more profound change to the existing legal regime will be required.

WP4: CCUS as an element for large-scale energy storage and conversion

For the first time a full CCU chain for the production of the eFuel dimethyl ether (DME) from captured CO_2 and electrolytically produced H_2 was demonstrated in ALIGN-CCUS. In addition to the development, construction and operation of the Power-to-DME plant, the demonstration comprised also the successful use of DME as a fuel for peak and back-up power generation and of OME (polyoxymethylene dimethyl ethers, which can be produced from DME) as a fuel for passenger cars. Both objectives, to present the potential of CCU regarding climate protection and to demonstrate its benefit and socio-economic value as an element for large-scale energy storage and sector coupling, have been achieved. Two patent applications on the technical and economic optimisation of the DME synthesis process and efficiency enhancement due to optimised integration of a DME-fuelled peak-power generation into power plant processes have been applied for.
The ALIGN-CCUS demonstrator was erected next to the CO_2-capture plant and in the immediate vicinity of the CO_2 filling plant, so that the CO_2 which is captured from the flue gas of the 1000 MW power plant unit could be used for the demonstrator (solvent in use was CESAR1).

The ALIGN-CCUS full chain CCU demonstrator at Niederaussem

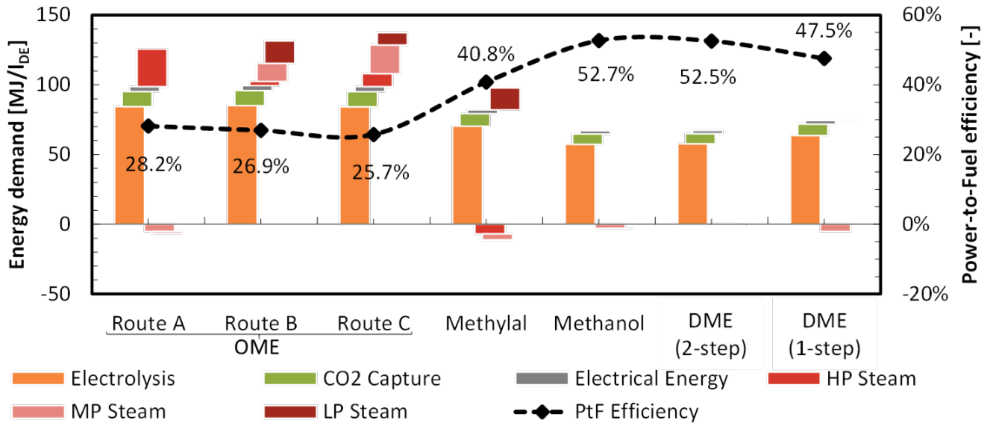
The Power-to-DME demonstrator comprises RWE's CO_2 capture and liquefaction plants and a CO_2 storage tank, the alkaline electrolyser from Asahi Kasei (140 kW_{el}, 22 kg H_2/d), Mitsubishi Power's units for CO_2 conditioning, gas compression and the DME synthesis (up to 50 kg raw DME/d), including a catalytic combustion unit from FZ Jülich for purge gas treatment and the gas supply system and tanks for storage of raw DME and waste water.
The first step for the engineering of the innovative direct synthesis of DME was the development and supply of a bi-functional catalyst by Mitsubishi Power. Both the formation of methanol as well as the dehydration of methanol to DME occur simultaneously at the surface of the catalyst. In this way only one reactor is needed for the DME synthesis, reducing the complexity and the number of components of the synthesis unit compared to a conventional two-step synthesis. Afterwards, the designed CCU synthesis unit was engineered, constructed, installed and commissioned by Mitsubishi Power at the test site after the permitting process and ground preparation was carried out by RWE. RWE was also responsible for connection of the demonstrator to the infrastructure for utility supply. Two generations of catalysts for the direct synthesis of DME have been developed by Mitsubishi Power. The first-generation catalyst was used in the small-scale "commissioning reactor" with approx. 5 % capacity, whereas the second-generation catalyst is used in the main reactor (two lines, each 50% capacity). The catalyst is coated on the surface of monoliths, which are integrated into the reactor.

Monoliths show low pressure losses, a very homogeneous flow and very low back mixing, resulting in a good mass transfer and they also allow an easy scale-up. Some sensitivity analyses regarding the effect of the H_2/CO_2 ratio on the yield, CO_2 conversion rate and product selectivity, process temperature and pressure have been carried out for the small-scale reactor set up to test the process in the industrial environment. It took one year to complete the mechanical work and commissioning after installation. However, the highly automated electrolyser showed no system errors and no irregular or additional maintenance work was necessary until now. During the commissioning, an operation time of more than 200 hours was reached with more than 80 start-ups and shutdowns. The advanced alkaline electrolyser can realize a wide operating range regarding the current density. While in general, for conventional alkaline technologies a limitation of the operation range regarding the current density is assumed (around 4.0 kA/m^2), the electrolyser in ALIGN-CCUS is able to operate efficiently between 1.0 kA/m^2 to 10.0 kA/m^2. At a current density of 4.0 kA/m^2 an excellent DC power consumption of less than 4.15 kWh/Nm^3 H_2 could be achieved. A special highlight is the implementation of a flameless purge-gas treatment system newly developed by FZ Jülich, as a flare system was not allowed at the power plant site due to legal regulations. The selected system design – consisting of 3 catalytic burners – allows to fulfil the local emission limits.

Since DME is gaseous under atmospheric conditions and has a lower heating value compared to diesel, changes need to be made in the fuel supply system of the peak-power generator. The fuel tank is pressurized at 5-8 bar depending on the ambient conditions. To determine the influence on the spray characteristics, optical investigations have been carried out in a high-pressure chamber. High-speed cameras revealed that the planned fuel injector with a two-piece injector needle connected via a coupler did not open correctly and the variations in the opening behavior were prohibitive for the use with DME. A new injector with a long needle was successfully used for further investigations and showed a constant opening behavior. Computational fluid dynamics combustion optimization focused on achieving a good air utilization at full load. Based on the results, a step-piston bowl was chosen. Considering the pre-carved bowl in the blank piston, the possible shapes were restricted considerably. Engine tests were first carried out with the standard diesel combustion system. For the DME application the fuel system was adjusted and the injectors as well as the high-pressure pumps were exchanged with new parts specifically designed for the use of DME. The fuel control system for the high-pressure system was changed from a value-controlled system to a pressure controlled one. After the first calibration of DME with the original piston bowls, the pistons were exchanged, and further tests and calibrations were carried out. The CFD optimized piston bowl showed a faster and more complete combustion and therefore better efficiency, but the resulting higher combustion temperatures and thus higher NO_X emissions could not be decreased as planned with higher exhaust gas recirculation (EGR) rates. The EGR system installed at this engine is retrofitted and does not allow high or even medium EGR rates. Since DME combustion has very low soot emissions, the Soot-NO_x conflict is eliminated and the EGR rate can be risen without emitting more soot and therefore the NO_X emissions can be reduced significantly. The maximum power of 250 kW of the engine operated with diesel was also reached with DME. Due to the different combustion behavior of DME and diesel, the surface temperature of the piston crown exceeded the design limit during peak load operation on DME. The engine torque was limited to 1300 Nm (i.e. 204 kW @ 1500 rpm) afterwards. It is expected that the engine can run continuously on DME at this load level, similar to diesel operation. Emission measurements for DME showed much lower particle mass and particle count, as well as lower CO and hydrocarbon emissions than diesel.

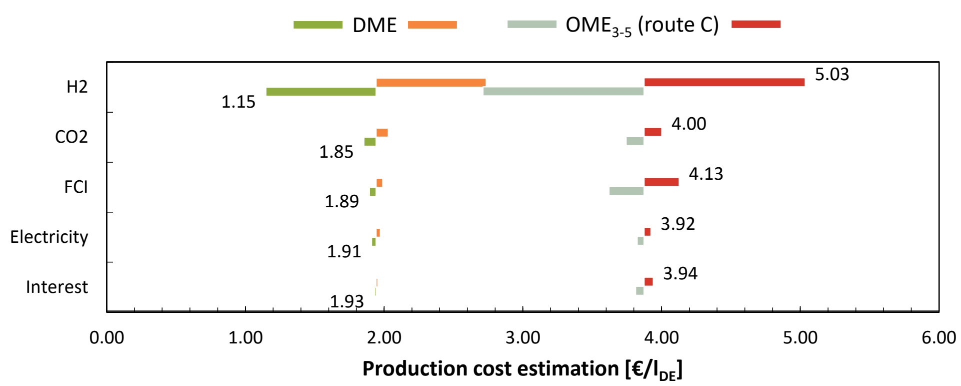
The physical and chemical properties of OME deviate considerably from those of conventional diesel fuel, thus necessitating engine modifications for the passenger car. To determine the influence on the spray characteristics, also here optical investigations have been carried out at an optical high-pressure chamber. Therein it was found that the increased volatility of OME leads to a shorter liquid penetration. Despite the high cetane number and thus short ignition delay, the lift-off-length is increased with OME in comparison to diesel. In combination with the molecular oxygen, this leads to a leaner mixture in the ignition zone and to a more concentrated heat release. CFD combustion optimization thus focused on achieving a good air utilization at full load while also mitigating the risk of damage from the high local spray-temperatures. Therefore, an open bowl without turbulence ring was chosen, as to lower heat intake and improve heat dissipation away from the critical surface. Still, a good air utilization could be achieved by adapting the rest of the bowl. The results from the engine tests with DME and OME have demonstrated that CCU is more than only climate protection.

Within ALIGN-CCUS reasonable process routes to produce alternative fuels were investigated and analyzed. The larger framework is set by the power-to-fuel approach, which utilizes renewable supplied hydrogen and recycled carbon dioxide. Especially for the synthesis of OME_n a unique modeling approach was developed, based on the differences in boiling points of the homologous series of OME_n. The comparison of energy demands and power-to-fuel efficiencies show that the production of OME_n is not efficient compared to methanol and DME. Considering different production pathways there is minor potential for further increase in efficiency and these potentials are not able to close the gap to the simpler fuel alternatives like methanol and DME. The simulation study has shown that the two-step synthesis of DME is slightly more efficient than the one-step approach. The calculations do not take into account the special features of the reactor type with monoliths selected for the DME synthesis plant, nor the optimization potentials with regard to product preparation and energetic process interconnection of the overall system. Without further waste heat utilisation, the best Power-to-Fuel efficiency for DME is 52.5%. All synthesis processes have in common that the energy demand for the electrolysis is dominating the energy demands.



Energy demand and Power-to-Fuel efficiency, HP: high / MP: medium / LP: low pressure steam.

The process simulations have been used to determine all required components as well as material and energy demands of the selected synthesis pathways. Further on, all components needed to be scaled so that appropriate cost estimations could be performed. The investment costs of the various production pathways are unified by the production capacity of 300 MW_{th}. With the base case values, the production costs of DME and OME_n are estimated to be 1.94 €/l_{DE} and 3.87 €/l_{DE}. To upgrade DME towards OME_n the base case price is nearly doubled, indicating a huge price gap between these two alternative fuels. The only effective way to reduce the overall production costs is to reduce the costs of hydrogen supply. It can be stated that OME_n is a high-cost alternative fuel.



Sensitivity analysis (-50 % and +50 %) of production cost for DME and OME_{3-5} (route C), base case parameters (4.6 €/kgH_2; 70 €/tCO_2; 0.0976 €/kWh; interest rate = 8 %)

Even if the lower cost by using existing infrastructure for fuel transport, supply and utilisation in cars are not considered, DME or methanol which are produced from CO_2 are already today cost competitive when all subsidies and tax exemptions for other climate protection measures in the transport sector are taken into account.

The cradle-to-grave Life Cycle Assessment (LCA) has taken into account all life cycle phases of the two investigated use cases (peak-power generation, passenger car), their emissions and material flows in and out of the system, starting from the natural resources and raw materials and ending with the end of life of the plants and hardware and wastes. Potential recycling and interdependencies with other products have been also taken into account. The LCA shows that global warming potential (GWP) of back-up and peak-power production could be significantly reduced compared to diesel fuelled engines or natural gas fired turbines. Prerequisite is that the stored energy comes from a source with low CO_2 footprint such as wind power. Using only today's grid electricity would increase the emissions instead. Transport using OME as fuel and replacing diesel is not viable in comparison with electric cars or conventional diesel fuelled cars regarding the GWP. However, DME produced from CO_2 of a lignite fired power plant and hydrogen with low CO_2 footprint would result in a GWP in the same range as an electric car supplied with wind power. The achieved results based on measured data assort well with data from the car company FORD and show that some studies which are only based on literature data are underestimating the positive potential of synthetic fuels. It was also shown that the mitigation of SO_x, NO_x and soot emissions by the use of synthetic fuels is not represented by the GWP. Therefore, also other impact categories should be taken into consideration (e.g. terrestrial acidification potential).

Promising option to reduce local emissions and the Global Warming Potential by use of the Power-to-X product DME in the electricity and transport sector (GWP diagramms – blue: CCU products from grid electricity; green: CCU products from wind power; red: fossil based fuels; yellow: e-mobility).

Especially two measures for a further technical and environmental optimisation of the CCU chain have been identified. Recycling of the exhaust gas of a DME fuelled power generator upstream of the capture plant and integration of its heat into the power plant (or carbon capture) process allows to significantly increase the overall efficiency and could reduce the GWP at the same time.

By CO enrichment of the feed gas the synthesis of methanol and DME can be greatly improved. Near complete selectivity to CO was achieved from atmospheric pressure up to at least 29 bar(a) in experimental campaigns using new developed multifunctional reactive sorbents (comprising a solid water sorbent impregnated with at least one metal capable of catalyzing the conversion of CO_2 from a H_2 / CO_2 gaseous mixture) in the reverse water-gas shift reaction.

WP5: Targeted CCUS activities in industrial clusters

The work in WP5 has advanced the development of CCUS in six industrial regions across five European countries. The work will support national and regional governments in future decision-making for industrial decarbonisation strategies within the targeted regions but has also draw together synergies from each case studies to help a more generic approach to cluster developments in Europe. Beyond the work in each individual cluster region (Tasks 5.1 to 5.5), Task 5.6 has taken a more overarching approach and utilised the research conducted in ALIGN-CCUS to develop more European wide advice documents regarding the business case for hubs and cluster developments.

WP5 overall has provided clarity on the future steps for hubs and cluster within the 6 industrial regions studied. The results of the research conducted in ALIGN-CCUS into these clusters has also allowed for modelling of embryonic CO_2 cluster infrastructure to be undertaken. Greater clarity can now be provided on the expected investment requirements and benefits for public and private actors of hub and cluster developments for CCUS.

Task 5.1 Teesside and Grangemouth

Work within Task 5.1, on the UK Teesside and Grangemouth cluster, has focused on the cost-reduction potential beyond the initial planned projects. This will help in the long-term decarbonisation plans for CCUS which are currently being developed by the UK government. The work in Task 5.1 has been conducted in line with the UK government's net-zero emissions plans and aims to support cost-effective deployment of CCUS in Teesside by 2030 and Grangemouth by the mid-2020s. ALIGN-CCUS has accelerated the 'next steps' to achieve capture and storage at tens of million tonnes CO_2 per year by: simulating multi-site storage options; assessing liabilities and recommending business models; and modelling cost-effective networks for transport and storage and CCS project business models. This ALIGN-CCUS work will inform UK decarbonisation beyond the industry remit and provides a wider perspective for policy and decision-makers. All deliverables were delivered as planned. CO_2 storage capacity and operations were modelled for the next sites to provide a growing and mature UK CCS industry to 2100 (D5.1.2a on Teesside and D5.1.2b on Grangemouth). Barriers to investment for CCUS component industries (costs, liabilities, and risk sharing) were also identified (D5.1.3). Recommended business models for public and private risk allocation and sharing for Teesside and Grangemouth were provided (D5.1.3) and cost-effective & flexible options, constrained by geology and geography, to inform choice of business model were also provided (D5.1.4).

Task 5.2 Port of Rotterdam

Task 5.2 regarding the Port of Rotterdam assessed the feasibility of developing a large-scale centralized natural gas decarbonisation facility with CO_2 capture and storage. The role of hydrogen production in potential decarbonization scenarios was reviewed and alongside potential production technologies. This allowed for the outline of planning requirements and transport routes and locations to be reviewed. Following the identification of potential hydrogen production scenarios, infrastructure requirements in the port to allow for hydrogen use and a central decarbonization facilitiy were identified. This work was developed alongside the existing H-Vision concept which has already been developed by industry in the Port of Rotterdam and provides a plan for expected hydrogen production and use development in the port. Overall, all deliverables were completed as planned: a description of required technology deployment and scope of facilities (D5.2.1); necessary modifications of existing infrastructure (D5.2.1); and modelling of the economic feasibility (D5.2.3).

Task 5.3 North-Rhine Westphalia

An assessment of possible CCU pathways in North-Rhine Westphalia, Germany, has also been undertaken in Task 5.3. A database of over 110 CO_2 sources has been developed along with the forecasting of DME demand until 2050. Modelling has been conducted to optimise DME plant location,

CO_2 source selection and potential network development. This has allowed for an investigation into the impact between developing a centralised on decentralised DME production facility. Major costs have been identified and their impact investigated, e.g. the type of capture technology and electricity supply requirements. Intermediate storage and the associated costs impacts have also been assessed. Overall, the work in Task 5.3 was completed as planned and allowed for CO_2 and H_2 sources to be identified and DME/OME demand to be reviewed (D5.3.1) and this has then allowed for CCU pathways to be identified (D5.3.2). This work has been conducted in collaboration with WP4 and the information collected from the demonstrator has been further developed.

Task 5.4 Grenland region

The design of a multi-user intermediate storage site in the Grenland region of Norway was investigated in Task 5.4. Three sources are located in close proximity in this region (Norcem, Yara and EGE) and ALIGN-CCUS has conducted a pre-feasibility investigation into the concept of a joint interim CO_2 storage site in Herøya Industripark near Porsgrunn. The effect that different full-chain approaches will have on the storage site design requirements have been assessed alongside a cost assessment of the full CCS chain with an intermediate multi-user storage facility. The work in this task was delivered as planned with the pre-feasibility design of an intermediate storage site (D5.4.1) and a follow-up report on the impact of up and downstream variables and the economic impact (D5.4.2).

Task 5.5 Oltenia Region

Source and sink matching was conducted for the Oltenia Region in Romania as part of Task 5.5. As part of this work major emitters in the region have been identified and data has been collected regarding their annual CO_2 emission volumes. Alongside this, utilization and storage options in the region (both on and offshore) have been reviewed. All this data allowed for an inventory to be produced, D5.5.1, on the identification of sources and sinks. Following this initial source and sink identification CCUS pathways were identified and potential transport options reviewed. This was then investigated in more detail regarding potential transport links, with all options reviewed including by rail, road, pipeline and ship in D5.5.2. All work was delivered as planned.

Tasks 5.1 to 5.5 focused on the six major industrial clusters and research was focused on making CCUS developments at a national level. Outside of these clusters though, the learnings from this research have a much wider benefit. Task 5.6 in ALIGN-CCUS was therefore intended to bring all these case studies together and identify synergies between their findings. Following interviews with the researchers involved with each of the Tasks 5.1 – 5.5, learnings have been developed regarding how commercial models can be developed to support CCUS hub and cluster development. A toolkit for action has been developed based on the overall learnings that can be taken for this hubs and cluster research as a whole. This toolkit (D5.6.1) can be applied to any industrial region embarking on a decarbonisation pathway. It is publicly available and designed to be used by governments and policy developers. This work can help identify existing advantages as well as conditions and requirements necessary to successfully provide access to the infrastructures and technologies required for successful CCUs development. The learnings for hubs and cluster developments were also developed into an easily digestible factsheet (D5.6.2) designed to be accessible to those with a less technical focus.

Overall, the work conducted in WP5 has been done in co-operation with all the other work packages in ALIGN, where developments regarding capture, transport and storage has also been undertaken in these WP5 cluster regions. These findings have been incorporated into the techno-economic modelling and assessments produced for each on these industrial clusters providing conclusions based on the most up to date data available. Although each of the industrial clusters has identified specific development and research needs, they are all centred around developing full-chain CCUS projects and have allowed for learnings to be defined relevant to all future CCUS hub and cluster developments.

WP6: Implementing CCUS in Society

The overall objectives of WP6 involved the reduction of non-technical risk for CCUS implementation by:

- Assessing public and stakeholder perception about CCUS, specifically towards industrial CCUS and CO_2 utilisation projects (Tasks 6.1 and 6.3);
- Developing theory-based, evidence-based communication and compensation strategies that instigate trust and have a positive effect on societal acceptance of CCUS (Tasks 6.2 and 6.3).

All WP6 deliverables and objectives have been successfully achieved incorporating additional linkages and exchanges between the WP6 tasks, with WP0 and experts from other ALIGN-CCUS WPs, with input from colleagues from other ACT/H2020 projects (e.g., ELEGANCY), as well as stakeholders from the field. The additional interaction greatly improved the relevance and quality of the work conducted.

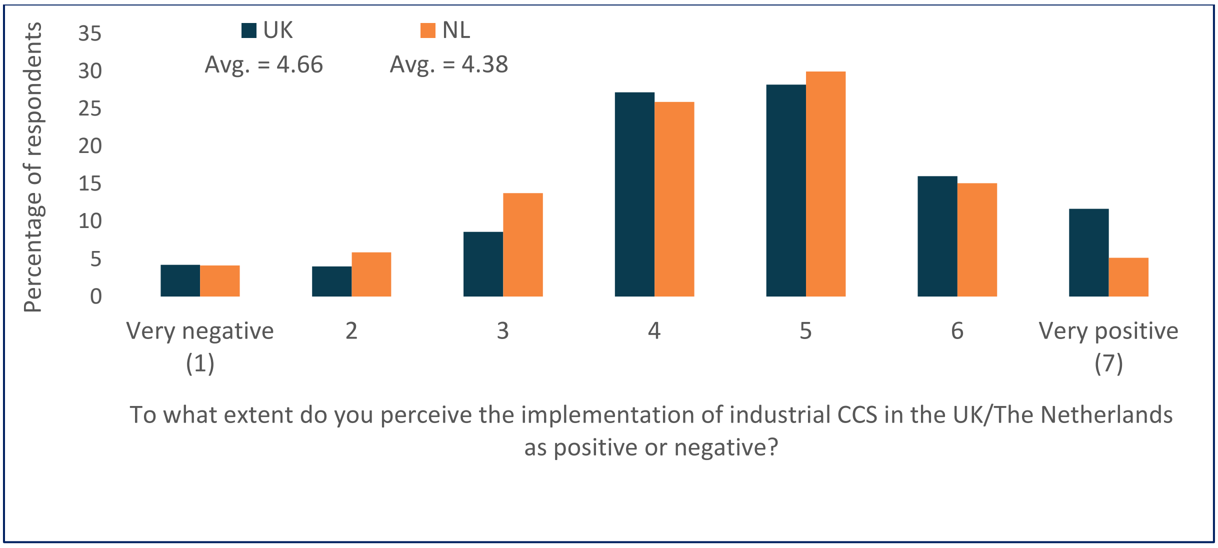
Overall, the WP6 results obtained provide insights in narratives and arguments used in the media, relevant stakeholders and their perceptions, and determinants of public opinion – this will help in making site selection decisions and developing effective public engagement strategies. Moreover, the WP6 research provides a set of lessons and knowledge gaps for community engagement and compensation in the context of CCS. These findings can provide a useful tool for researchers in this field looking to close knowledge gaps as well as stakeholders (e.g., project developers; authorities; community engagement managers) wanting to understand how to effectively make use of community engagement and community compensation in the CCS context.

Task 6.1: Informed public opinion about industrial CCUS

Understanding public perceptions is important in de-risking commercial employment of CCUS. In Task 6.1 public opinion of industrial CCUS and relevant underlying explanatory variables have been examined by means of an informed polling survey conducted among citizens in the UK and the Netherlands (N = 1961). The information provided in the survey was drafted and revised by very helpful feedback obtained through an expert consultation round with ALIGN-CCUS partners and external experts.

The results of the survey show that citizens in the UK and the Netherlands have moderate awareness and limited knowledge about industrial CCS. After receiving extensive information about the topic, citizens' opinions about industrial CCS on average were found to be neutral to slightly positive (see the figure below). Awareness and knowledge were found to be somewhat higher in the UK than in the Netherlands, and opinions about industrial CCS were found to be somewhat more positive in the UK than in the Netherlands.

The study not only looked into opinions about industrial CCS, but also into which aspects and associated outcomes of industrial CCS raise concerns or are valued by citizens, and how they affect their opinion. The results of the survey show that citizens from both countries express concerns about the safety of industrial CCS (the safety of onshore and offshore pipeline transport; the safety of offshore storage). Given the negative perception of the safety outcomes of industrial CCS, alleviating these concerns likely requires more intensive engagement between citizens and experts. For example, this could involve co-creating monitoring systems and procedures together with citizens and other stakeholders exposed to the (perceived) risks created by CCS infrastructure. Our findings further show that citizens from both countries appreciate potential economic benefits of industrial CCS implementation, and the impact on CO_2 emissions. These perceptions of environmental, safety and economic outcomes of industrial CCS combined to an important extent predicted citizens' opinion about industrial CCS. Socio-demographic factors (e.g., age, gender, education) had relatively little predictive value, by contrast, whereas opinions were significantly influenced by citizens' trust levels in industry and scientists. Our results show that citizens who have more trust in industry in the context of industrial CCS, are more positive about industrial CCS. The results also how that citizens' trust in industry is not given and may need to be build.

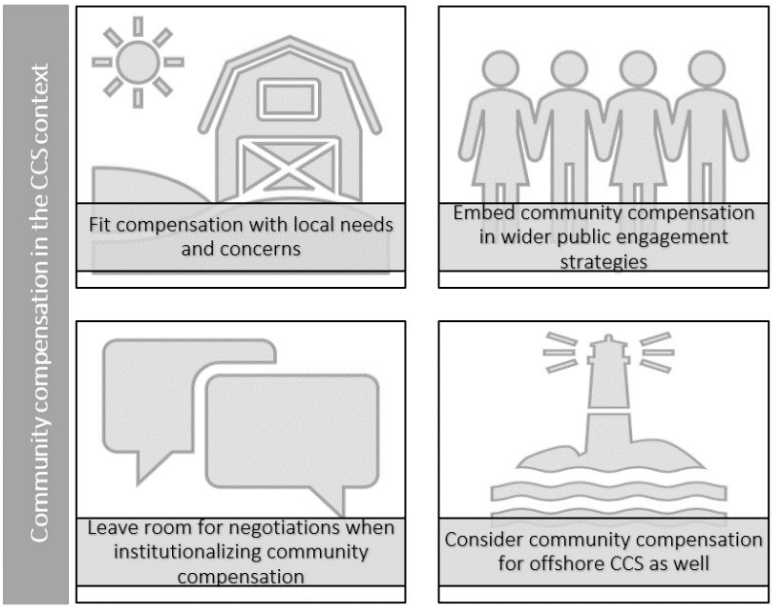


Public opinion about industrial CCS implementation in the UK/The Netherlands (N = 1961).

Task 6.2: A fair distribution of costs and benefits: Designing effective engagement and compensation strategies

Community engagement and community compensation are important instruments to build trust relationships and foster public support for planned and future industrial CC(U)S projects. The main aim of Task 6.2 was to identify and understand success factors and pitfalls in community engagement and community compensation for CCS projects and to identify and close relevant knowledge gaps. We used a three-step approach to reach this aim, using a mixed-methods approach.

As a first step, we conducted a desk-based review on compensation practices and guidelines for subsurface activities, energy and infrastructure developments in EU and non-EU countries (among which the Netherlands, UK, Germany, and Romania). This review resulted in four lessons and knowledge gaps regarding the implementation of community compensation in the context of CCS, summarized in the figure below.



Lessons on community compensation in the CCS context. Figure taken from Boomsma et al., 2020.

Step 2 was designed to close knowledge gaps coming out of the review in Step 1, to identify and understand success factors and pitfalls in community engagement and community compensation, and to share and validate relevant findings with key stakeholders. To this end, we conducted 30 semi-structured interviews with community engagement managers working on CCS projects (former or current projects) and other relevant non-CCS projects in the Netherlands, the UK and Romania. A follow-up workshop was held with the interviewees in the Netherlands to validate and share the interview findings. The results of the interviews and workshop show that environmental engagement managers have valuable expertise and experience when it comes to the implementation of local projects. Related, the results also show that useful lessons can be learned from non-CCS projects when designing engagement and compensation strategies in the context of CCS. The results from the Task 6.2 interviews and workshop further suggests that community engagement and compensation preferences, views and practices as expressed by community engagement managers interviewed in the Netherlands, the UK and Romania overlap to an important extent, but also that each project is unique, and that country-specific and local contexts need to be considered.

Finally, Step 3 consisted of two experimental survey studies designed to close knowledge gaps and test the effectiveness of different community compensation schemes in different European countries. The first experimental survey study was conducted among citizens in the Netherlands, the second experimental survey study was conducted among citizens in the Netherlands, the UK, and Romania. The results of the experimental studies show substantial overlap in relative preferences for community compensation measures among citizens in the Netherlands, the UK, and Romania, but also relevant differences between countries when it comes to CCS acceptability and the evaluation of compensation measures.

Task 6.3: Changing the conversation about CCUS in Europe

Task 6.3 consisted of two subtasks. Task 6.3.1 aimed at examining stakeholder perceptions of CCUS in Europe, in particular in Germany and Romania: Task 6.3.2 focused on testing and developing new core messages.

In Task 6.3.1 we examined stakeholder perceptions of CCUS in Germany and Romania. We did so by means of desk research and 32 semi-structured interviews conducted in Germany and Romania. The results show that in Germany, the stakeholders interviewed support CCU, especially for heavy industries, but are negative towards CCS. In Romania, by contrast, the stakeholders interviewed support both CCU and CCS, but CCS was considered more feasible and important for coal-fired power plants. In both countries the stakeholder interviewed expressed concern about the high cost of implementation of CCS and unclear political support. Stakeholders in both countries further indicated that CCUS acceptance-building measures among the public are important.

In Task 6.3.2 we conducted a literature review, media analyses (in Germany, the Netherlands, and Romania) and website analyses (in Germany, the Netherlands, the UK, and Romania) to identify current and past conversation about CCUS in society. The results of the media and website analyses show that coverage levels and type of discourse differ between the four countries. The results also show that similar arguments are used for and against CCS. For example, proponents state that CCS is a sustainable and proven technology, whereas opponents present CCS as not sustainable and unproven. This potentially makes it difficult for the public to form an opinion about an already complex subject. Further, results showed that CO_2 utilisation attracts little media coverage so far. With regard to the creating and testing of new messages, based on the literature review and the media/website analysis a focus group study among citizens in Romania was conducted, as well as a quantitative experimental study on message framing (e.g., gain vs. loss framing) of industrial CCS among citizens in the UK. Regarding the focus group study, the results showed that participants in the 'industrial area focus group' considered both environmental and economic benefits (maintenance of industrial activity) important, whereas participants in the 'non-industrial area focus group' considered environmental benefits more important. In this study, we also tested four potential CCS messages, and found that what was key for the focus group participants was that messages are clear, accessible, and appeal to citizens' personal interests.

4. Project Impact

Project Impact of ALIGN-CCUS per country

The Netherlands
In the Netherlands the focus around CCUS is focussed on the Waste to Energy (W2E) sector and the storage activities around the North Sea area.

The W2E sector is investing a lot into CO_2 capture. With AVR having the first full scale CO_2 capture project running in Europe and Twence linking up with Aker Solutions to build a full-scale plant, the sector is in the frontline of implementing CO_2 capture in Europe. Also HVC has a capture pilot plant and is looking at scaling up. Many others have expressed their interest in capturing CO_2. In the Netherlands there is quite a unique situation that the greenhouses have a demand for CO_2 to increase plant growth. Multiple projects are supplying CO_2 to the greenhouses which prevents that greenhouses make their own CO_2 by burning fossil fuels. TNO and other Dutch companies are involved in multiple projects to support the activities and to accelerate the implementation. Knowledge is shared in workshops, where the sector exchange results and openly discusses issues. This knowledge sharing is supported by RVO (the Dutch Enterprise Agency). In the work performed the knowledge gained in ALIGN-CCUS is used and further developed.

Also, for CO_2 storage there are projects being developed in the Netherlands. The two most important being: Porthos (https://www.porthosco2.nl/) and Athos (https://www. athosccus.nl). Porthos is preparing a project to transport CO_2 from industry in the Port of Rotterdam and store this in empty gas fields beneath the North Sea. Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage. The Athos project aims to develop a public CO_2-distribution network in the North Sea Canal area, enabling the capture and transport of CO_2, for usage or to be stored in empty gas fields under the North Sea.
Athos is an abbreviation for Amsterdam-IJmuiden CO_2 Transport Hub & Offshore Storage. Companies in the respective clusters can use the network to store their captured CO_2.
In ALIGN-CCUS important work was done to support the development of these two projects. Recently, the European Commission has nominated Porthos and Athos for a subsidy of respectively 102 and about 15 million euro for further development.

The Dutch initiative VOLTACHEM (https://www.voltachem.com/) is developing technologies to utilise CO_2 for the production of renewable fuels and chemicals like formic acid. A consortium lead by TNO has recently won a H2020 project named TAKE OFF, with the aim to develop synthetic fuels for the aviation industry. Some of the project partners now active in WP4 of ALIGN-CCUS have an important role in that project.

Norway
The Norwegian partners have been involved in all WPs except for WP4, which is symptomatic for the focus in Norway being more towards CCS than CCU solutions. However, it may change in the future as utilization may become an alternative or combined with storage to make it more attractive for economic reasons. Nevertheless, the work has been very important in many respects and will hopefully get a longer-term impact through near term utilisation of the results. For the research institutes from Norway the knowledge gained in dynamic operation and online measurements (WP1) is mostly taken further in follow up projects like LAUNCH (ACT), NCCS and REALISE (H2020) as well as in a new project initiative aimed at being funded by ACT3 (lead by SINTEF). Important lessons learned were in the CO_2 transport (WP2). The findings have been further followed up through the CO2LOS II project ending in 2020, and to be taken further in a CO2LOS III project that is under preparation. The results have also been used as input for an ACT3 application with TNO as lead. Regarding Storage, the Norwegian partners in ALIGN-CCUS have outlined and discussed possibilities for a large CO_2 storage hub in the region around the Northern Lights storage site. This Horda Platform CO_2 storage hub could likely serve a significant fraction of the storage needs for Scandinavia and Northern Europe. The concept is already

being further developed in ongoing work in NCCS. Acquired knowledge from the ALIGN-CCUS project has already been used in the ACT2 REX-CO2 project and a proposal with wide industry support, recently submitted to the ACT3 call. For the Longship project, the approach taken in ALIGN-CCUS has proven useful. Locally the cluster, in cooperation with SINTEF, is developing a project application to CLIMIT for how to capture and transport all the CO_2 in the region from a common hub. The tool Bellona has developed in ALIGN_CCUS to follow when evaluating individual pathways to deploying CCUS is expected to play an important part in Bellona's future engagement on developing CCU and CCS projects across Europe. A first instance for application is likely to be the 'Building momentum for the long-term CCS deployment in the CEE region' project, financed through the EEA Norway Grants. Also, the research conducted in WP6 has provided valuable information about the perceived role and necessity for CCUS. As such, it will provide valuable background for the development of the messaging intended for those same stakeholders in the future. For IFE the ALIGN-CCUS findings initiated more testing in the KDC III project and are presently used in the design and construction of a new ECCSEL infrastructure for testing, amongst other, ship transport conditions. For TCM the knowledge and competence gained through ALIGN-CCUS is the cornerstone in their advisory activities. Building on the knowledge gained from the ALIGN-CCUS project, TCM aims to test different flue gas sources and under operating conditions that are of value for the industry in order to reach their climate goals. Some projects have already performed specific tests at TCM to answer industry specific questions. The USN Raman solvent monitoring tool was demonstrated for 540 operating hours at pilot scale operation conducted by the Pilot-scale Advanced CO_2 Capture Technology (PACT) facilities, UK, in ALIGN-CCUS. The USN Raman tool was upgraded for determination of CO_2 loading, amine strength and monitoring of oxidative degradation products (heat stable salts). This upgrade was successful despite the rapid and progressive solvent colour change of MEA (from transparent to dark brown). Both NORCEM and Yara will utilize the results from ALIGN-CCUS in further work with CCS and a hub in Grenland for collecting captured CO_2 from many of the industrial plants in the Grenland area may be realized through future projects.

Germany

Especially the demonstration of the technical feasibility of the full CCU chain and the results of ALIGN-CCUS attracted a lot of attention at German stakeholders. Especially the delivered facts about the potential of synthetic fuels - which are produced from CO_2 - for climate protection, emission reduction, long-term energy storage and security of supply contributed to the public discussion about the transformation of the energy supply system in Germany. The project was successfully presented in meetings with representatives of (inter alia) the Federal Ministry for Economic Affairs and Energy, the Ministry for Economic Affairs, Innovation, Digitalisation and Energy of North-Rhine-Westphalia and the Energy Agency of North-Rhine Westphalia.

The industrial partners of ALIGN-CCUS are strongly involved in further projects on Power-to-X technologies and in the field of synthetic fuels. ALIGN-CCUS has contributed valuable input for future projects targeting commercial large-scale applications, but also projects aiming to advance the technology by using the lessons-learned in ALIGN-CCUS. All partners are involved in follow up-projects of ALIGN-CCUS, like the EU-funded project TAKE-OFF on jet fuel production (using the ALIGN-CCUS demonstrator) and national funded projects on the use of the synthetic fuel DME in fuel blends (DMEplusX) and concept studies for large-scale Power-to-X plants.

United Kingdom

There has been marked increase in recognition and need for CCS to reduce process emissions from industry and for domestic and commercial heating by large-scale reformation of hydrogen and CCS in the UK during the ALIGN-CCUS project. ALIGN-CCUS proposed research, based on emerging concepts and published strategies, has become of increasing relevance and interest with announcement of a net-zero emissions strategy and government support for decarbonisation of industrial clusters in 2018. Two of the five UK clusters, Teesside and Grangemouth, identified for industrial decarbonisation were investigated in ALIGN-CCUS to reduce the cost of CO_2 transport and storage and assess a public-private business case, including sharing of risks and liabilities. The research in ALIGN-CCUS has stayed very closely in-step with UK emissions reduction ambitions, including incorporation of plans for CO_2 storage by the Net Zero Teesside Project via TVCA and the H21 North of England Project from Equinor. Project results have been presented, at stakeholder request, to the Climate Change Committee and Oil and Gas Authority.

The Storage Readiness Levels terminology is already in informal use, as noted at the CO_2 storage plenary presentation by industry at the Mission Innovation meeting June 2019 in Trondheim. A journal paper presented from the finalised ALIGN-CCUS deliverable was submitted to International Journal of Greenhouse Gas Control. Revision of the submission in response to reviewer's comments is approaching completion. An abstract on the finalised SRLs framework was submitted and accepted for oral presentation at the GHGT-15 conference in March 2021.

Early research findings on the investigation of the suitability of offshore infrastructure, development of a methodology for screening for use and recommendations on data types and availability were submitted to Oil and Gas Authority in September 2019. There has been stakeholder interest from industry (Net Zero Teesside) and regulator (The Crown Estate) in the modelling of 'next stores' for the UK ALIGN-CCUS clusters, and further strategic modelling to assess CO_2 storage for the Teesside and Humberside industrial clusters included in research proposals. During confidential discussions an industry contributor noted their future intentions for multisite storage beyond current plans would be accelerated and cost reduced by research based on the ALIGN-CCUS selection, appraisal and simulation of CO_2 injection. Equinor joined the ALIGN-CCUS project as a supporting partner in 2019 specifically to contribute to and access the findings of the CO_2 storage assessment for Teesside to inform their work for H21 North of England.

Emerging findings from the business case and sharing of risks and liabilities considered in the ALIGN-CCUS UK case studies were submitted to BEIS in their consultation on CCUS business models in September 2019. The finalised results have been of interest and presented to industry, National Grid, and presented to the Cabinet Office in 2020.

Romania

In Romania, the use component in the CCUS chain is less present in the discourse of stakeholders, since the variants of projects considered so far relied on onshore storage. Further, the engagement of stakeholders in potential CCUS projects is modest, due to the fact that the decision factors are not perceived as making a priority from the CCUS development. Moreover, the main challenge identified by stakeholders referred to the important funds needed for the implementation of CCUS projects, funds that could not be provided by the industrial units. Therefore, even if the greatest part of stakeholders (among the 17 stakeholders interviewed in WP6) expressed their positive opinion and support for CCUS, they also mentioned that they are sceptical with regard to the future perspectives of CCUS in Romania.

However, the experimental survey findings among citizens in Romania proved that the Romanian respondents presented a higher level of acceptability for CCUS implementation in comparison with the respondents from other countries. Also, the focus group results showed that the implementation of CCUS projects could be accepted by publics if clear and honest information is delivered in a proactive manner.

Update of impact table from the proposal on project impact

The expected results and foreseen impacts of ALIGN-CCUS are presented per WP in the table below:

WP	Key expected results	Impacts	Final result
WP1. Capture	Complete characterisation of aerosol-based emission and demonstration of countermeasures at TRL 6/7	Validation of the performance of proposed countermeasures for aerosols at industrial scale	Characterisation: While there are still some gaps, this has been achieved. NTNU's model gives reasonable prediction of aerosol-based emissions, meaning the mechanisms of growth are well described. The countermeasures are well described. Demonstration: Here we also have some gaps. The tests performed at RWE were too short to have conclusive, irrefutable proof of the efficiency. But the demonstrations and validation of reduction in emissions and number of particles were achieved.
	Ensuring solvent consumption below 0.3kg amine/ton capture at TRL 6	Significant OPEX reduction compared with published solvent consumption and reduction of waste streams	For both tested solvents unique long-term operation >12,000 h was demonstrated. Without any countermeasures, the solvent consumption is slightly higher (0.45 kg for CESAR1 and around 0.4 kg for MEA), but with efficient emission and degradation countermeasures it is demonstrated that these numbers can be reduced without drastically increasing the capture costs.
	Guidelines for reliable and cost-efficient operation at varying feed conditions and CO_2 product requirements	Improved CO_2 capture plant design for flexible operation and niche applications.	We have achieved this. We have looked into amine and ammonia emissions. The cost-efficiency is evidenced in D1.4.3. Also, the effect of dynamics on solvent emissions and the possible adaption of countermeasures is done. Adaptation of countermeasures does not seem to be needed.
WP2. Transport	Derive cost estimates and benchmarks for CO_2 shipping and offshore unloading with reduced uncertainty	Improved understanding of the business case for shipping and direct injection	Techno-economic analyses showed that for all the studied configurations the low-pressure option has slightly lower cost than the medium pressure option. For the Norwegian North Sea example injection from ship was shown to be the least cost option, followed by injection from offshore pipeline while FPSO options showed the highest cost.
	Quantification of the impacts of batch-wise injection on the integrity of the storage system	Allow operational guidelines to be developed for batch-wise injection	Batchwise injection of cold CO_2 can give rise to thermal contraction of well materials, hydraulic fracturing of caprock and precipitation of salt.

WP	Key expected results	Impacts	Final result
			Modelling has produced a basis for identifying key performance indicators for safe and efficient injection conditions.
	CO_2 specifications expected from pilot-scale post-combustion capture systems are evaluated in dense-phase CO_2 corrosion lab	Allow the identification of an optimum balance between stream composition and transport infrastructure needs	Lab experiments and interaction between work packages in ALIGN-CCUS has produced "acceptable" CO_2 specifications and pointed to the capture end of the chain as being the critical part regarding CO_2 quality.
	A real-options multi-period CCS network optimisation model including capture from power and industry, energy storage and conversion is developed	Improved cost-benefit analysis capabilities for planning full-chain CCUS projects and CCUS clusters	The real-options model considers pipeline infrastructure in combination with ships and lorries and accommodate intermittency in CO_2 supply and integration of small sources. The model is in fact an investment decision framework supporting larger flexibility and cost efficiency in the capture, transport and storage networks.
WP3. Storage	Provide a classification framework for storage readiness levels benchmarked against existing storage sites	Increased investor confidence in timeframe and resource needs for follow-on storage development.	Application of the classification framework highlights sites at contingent storage resource and permitted/permit ready sites in the UK (4), The Netherlands (3) & Norwegian (3) North Sea. The experience of site investigation and permitting illustrates to stakeholders and investors the range of costs and timescale for appraisal and permitting of a storage site. In practise, the duration is somewhat shorter (<2 to 4 months) than published estimates (2 to 6 years).
	A portfolio of selected storage sites in the UK, Netherlands and Norway to provide certainty on storage for ALIGN-CCUS clusters	Enables FIDs on transport and storage infrastructure and supporting development plans for storage roll-out.	Profiles for CO_2 supplied in the coming decades from the ALIGN-CCUS industry clusters in the UK, the Netherlands and Norway, illustrate European need for gigatonne-scale storage in the North Sea. The options selected and appraised for the four ALIGN-CCUS North Sea clusters are all sufficient to store captured CO_2 at rate of tens of millions of tonnes per year.
	An asset register of existing North Sea oil and gas infrastructure and assessments of their suitability for re-use for CCUS projects	Supports decommissioning policy and regulation for transport and injection infrastructure.	A methodology developed in ALIGN-CCUS has applied to identify infrastructure suitable for re-use of hydrocarbon field stores for Rotterdam and saline formations for the Teesside, Grangemouth and Grenland clusters. Technical methods have been defined to address and manage temperature and pressure constraints associated with re-use of low-pressure depleted

WP	Key expected results	Impacts	Final result
			gas fields. Three legislative scenarios have been identified to enable infrastructure re-use. An interim entity or 'operator of last resort' is proposed to maintain selected infrastructure until needed for CO_2 storage.
WP4. Re-use	Demonstration of the full CCS/CCU chain	Proven feasibility and viability of a utilisation chain, increases public awareness and acceptance of CCS/CCU as a climate protection technology	The worldwide first demonstration of a full CCU chain and the use of the CCU product DME for peak-power production and OME in a personal car attracted a lot of international attention. A blueprint was provided for carbon re-use and sector coupling as an element of large-scale energy storage with high energy density by converting CO_2 into fuels.
	Understand the additional multi-sector benefits of establishing a CCUS chain producing low-emission transportation fuels	Quantifies the potential socio-economic effects of CCS/CCU beyond climate protection by intelligent coupling of the sectors energy, industry and transport.	The techno-economic analysis in ALING-CCUS showed the cost competitiveness of CCU products like DME or methanol in the energy and transport sector with other climate protection measures taking into consideration tax exemptions and subsidies for these technologies. It was shown that CCU fuels would allow an evolutive transformation of the existing supply systems and traffic by using the available infrastructure instead of an expensive disruptive approach.
	Techno-economic optimisation of the CCU demonstrator technology	Enhances the chance for accelerated implementation of CCU due to better economic performance.	The high potential to further optimise the demonstrated technology manifests in two patent application (synthesis optimisation by CO enhancement in the feed gas by multifunctional sorbents for the adsorptive removal of water from the processed gas; advanced integration concept of DME-fuelled back-up power production by CO_2 recycling and waste heat utilisation).
	Quantify the environmental performance of a full CCUS chain using data derived from actual operation	Makes the advantages of CCUS transparent in comparison with other competing climate protection technologies.	The "cradle to grave" Life Cycle Assessment showed that the use of CCU products like DME and methanol which are produced from captured CO_2 is competitive with other climate protection measures regarding the Global Warming Potential as long as hydrogen with a low CO_2 footprint is used (e.g. from electrolysis with wind

WP	Key expected results	Impacts	Final result
			power). Additionally, it was demonstrated that the use of DME or OME as fuels for combustion engines could significantly reduce the local emissions of soot, sulphur and NO_x in the traffic and energy sector.
WP5. Industrial clusters	Provide a set of actionable development plans for targeted CCUS activities in 6 key industrial clusters across the EU	Supports national and regional governments in decision-making for industrial decarbonisation strategies	All 6 industrial clusters have provided development plans, or highlighted key areas for future development as part of numerous deliverables. All the clusters are at various stages of deployment but the work conducted will help local governments develop well-informed plans for CCUS cluster deployment.
	Develop commercial models for embryonic CO_2 cluster infrastructure using results from pilot-testing and optimisation modelling completed in ALIGN	Greater clarity on the expected investment requirements and benefits for public and private actors	Task 5.6 has synthesised the work conducted in WP5 to provide clarity on cluster development methodologies and future requirements to form investment strategies. A decision support tool is now publicly available to support decision makers on cluster development options.
WP6. Society	Understanding of public and stakeholder perception concerning CCUS projects in industrial applications, including CO_2 utilisation	Provides tools for making site selection decisions and developing effective consultation and communication strategies	- Insight in (underlying factors of) public perception of industrial CCS in the UK, the NL and Romania through (informed) survey studies. - Insight in (determinants of) stakeholder perception of CCUS in Germany and Romania through desk research and stakeholder interviews.
	Evidence-based insight in best practices regarding the use of compensation schemes for CCUS projects	The identified success factors and pitfalls support project developers and national governments in designing effective compensation strategies	Theory-based, evidence-based insight in best practices and pitfalls regarding community engagement and compensation: based on an academic and policy review; interviews conducted with community engagement managers in the UK, NL, and Romania; a workshop held in the Netherlands; and experimental survey studies conducted among citizens in the UK, NL and Romania.
	Development and testing of new communication materials for CCUS	Provides strategic elements for a dialogue with society about the need and necessity of CCUS	A literature review, media analyses and website analyses provided insight in past and present positioning of CCUS in Germany, the UK, the NL and Romania. Focus groups conducted in Romania and an experimental survey study conducted in the UK tested specific elements in CCUS communication among citizens, providing relevant insights in the

WP	Key expected results	Impacts	Final result
			effectiveness of specific (new) messages in the context of CCUS.

Gender equality in ALIGN-CCUS

Accelerating the commercialisation of CCUS is not gender sensitive. Nevertheless, the project, the consortium and the participants' organisations were committed to the promotion of equal opportunities between men and women. In ALIGN-CCUS, the leadership of the R&D work packages was balanced 50/50 between male and female project participants. WP1 (Hanne Kvamsdal), WP3 (Maxine Akhurst) and WP6 (Emma ter Mors) were led by female experts. The Work Package lead from WP5 has been taken over by a female expert (Lydia) in the last year of the project. In WP2, part of the coordination has been picked up by a female expert (Ragnhild Skagestad). In meetings one third of the participants were female experts.

5. Collaboration

Cooperation within ERA-NET ACT

CCS Social Science Network

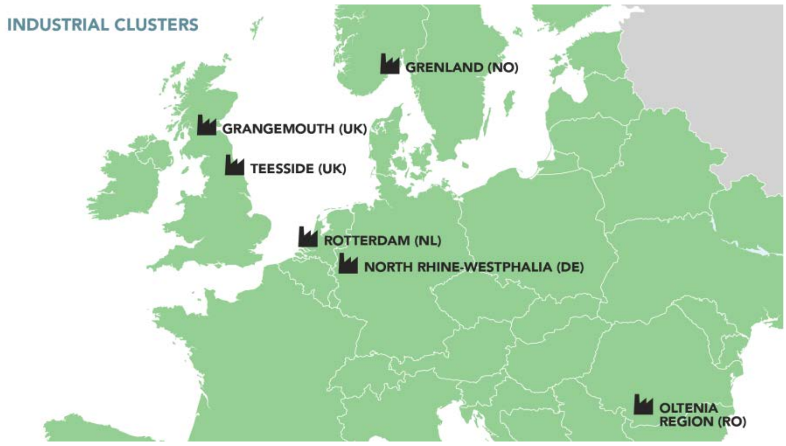
During the early knowledge exchanged meetings of the first round of ERA-NET ACT projects, it was identified that all first-round projects have objectives with regards to social science and public perception. Members of WP6 of ALIGN-CCUS identified scope for collaboration and coordination of efforts, and the sharing of expertise, and thus initiated a quarterly teleconference between the projects. By now, 13+ ACT/H2020 projects (e.g. ALIGN-CCUS, ACORN, ELEGANCY, ECO-BASE, ENOS, STRATEGY-CCUS, PerCCSeptions, GENESIS, DIGIMON, C4U, REX-CO_2) take participate in these calls, and the Network has almost 70 members. A shared online environment has been established to allow sharing of information between projects.

Cooperation with other ERA-NET ACT projects in the other Work Packages

Exchange of information is encouraged for all Work Packages. More specific, for WP3 there is cooperation with ACORN, PreACT and ELEGANCY en in WP5 also with ELEGANCY.

European Trans-national collaboration on CCUS

A global rate of decarbonisation, consistent with the Intended Nationally Determined Contributions (INDCs) of the 2015 Paris agreement will require rapid acceleration of greenhouse gas (GHG) mitigation efforts post 2020 to retain warming to 2°C.[2] The INDC submitted by the EU committed to a binding target of at least a 40% reduction of GHG emissions by 2030, compared to 1990 levels.[3] This will require the deep decarbonisation of not only electricity supply but residential heating, industrial heating and process emissions, all areas where CCUS is anticipated to have a significant mitigation role.



Industrial clusters covered in the ALIGN-CCUS project

CO_2 emissions are not limited by countries borders and it is evident that international collaboration is essential to meet the goals mentioned above. In ALIGN-CCUS, the focus was to work on the individual chain elements and to provide actionable decarbonisation blue prints in six industrial regions across five EU countries (see figure above) in which CCUS enables low-emission industries, through geological storage or through utilization of CO_2.

Now ALIGN-CCUS is coming to it's end we see a big increase in activity in the various specified regions: Grangemouth and Teesside have advanced plans for decarbonisation of their regions. The important Longship project in Norway has been granted. In the Netherlands Phortos and Athos are under development and have received significant funding from Europe. In Germany there is a boost in

[2] Rogelj, Joeri, et al., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature*, *534*(7609), pp.631-639.

[3] European Commission, 2015. Intended Nationally Determined Contribution of the EU and its Member States. Please see here.

research on CO_2 utilisation. Although still on a lower TRL level, there are many projects defined. The H2020 project TAKE OFFF has quite some partners that were also active in ALIGN-CCUS. In Romania, there is still work to be done to further accelerate the implementation of CCUS, but important steps are made and the knowledge developed in ALIGN-CCUS is available to support implementation.

6. Dissemination activities

TNO and experts from the Scottish Carbon Capture & Storage (SCCS) teamed up in delivering the dissemination activities from ALIGN-CCUS. One of the first actions was to establish the brand ALIGN-CCUS in the CCUS community. This was done by setting up an advanced website and using social media like LinkedIn, Twitter. ALIGN-CCUS also has its own YouTube channel.

Besides keeping track of the dissemination activities like papers and conference presentations, publication was also actively pursued by encouraging people from the consortium to write blogs for the website. Also, several movies have been made to promote ALIGN-CCUS.

Approach

Effective communication and dissemination (C&D) were cornerstones of ALIGN-CCUS, with activities and processes defined at the outset that allowed for flexibility and creativity throughout the project. With the project now completed, the C&D record shows that ambitions were realised which, additionally, set a benchmark for future projects. In some instances, the WP0 team took an experimental approach. This proved invaluable when the COVID-19 crisis prevented public events, which meant that final dissemination activities had to be reconfigured for a wholly digital arena. An outstanding feature of the project's C&D work was exemplary cooperation among the project partners, borne out by a proactive approach to supporting the WP0 team and a willingness to share and develop ideas to their conclusion.

Website & newsletters

Website attention

A dedicated website – www.alignccus.eu – was developed and delivered by SCCS, with unique project branding and graphics created by the project lead, TNO. The website went live at the start of the project and remained a focal point throughout the project for news and other developments, events, project and partner information, funding details and social media links. In three years, over 42,000 new users visited the site for more than 45,000 sessions. There were also more than 73,000 individual page views by visitors from the project's five target regions as well as Japan, the US, France, Italy and Spain. The site now serves as an accessible repository with search functionality for all research outputs, and a legacy for the project.

There were a total of 17 news/feature stories, including:

- *Building public support for CCS with community compensation* (October 2020): http://alignccus.eu/news/building-public-support-ccs-community-compensation
- *Getting to grips with CO_2 transport for offshore storage* (March 2019): http://alignccus.eu/news/getting-grips-co2-transport-offshore-storage
- *Capture milestone boosts CO_2-to-fuel research goal* (February 2018): http://alignccus.eu/news/capture-milestone-boosts-co2-fuel-research-goal

There were a total of 5 blogs, including:

- *Passing the 'relay baton': findings from our focus on CO_2 storage sites* (May 2019): http://alignccus.eu/news/blog-passing-%E2%80%98relay-baton%E2%80%99-findings-our-focus-co2-storage-sites
- *Why do public responses to CCUS matter if CO_2 is stored offshore?* (August 2018): http://alignccus.eu/news/blog-why-do-public-responses-ccus-matter-if-co2-stored-offshore

Newsletters

Branded e-newsletters were created using Mailchimp and circulated to around 230 subscribers (gathered via website sign-up) every six months. A total of six newsletters were issued, which played a key role in keeping interested parties up to date with project developments and knowledge sharing events, such as webinars. The newsletter archive can be found here: http://alignccus.eu/news/past-newsletters

Social media

Twitter (@alignccus) and LinkedIn (@ALIGN-CCUS) were key for attracting and building interest in ALIGN-CCUS through sharing videos, news, research results and other media/material (see *Project Quarterly reports* for greater detail). Both played a strong role in promoting events. They also enabled "conversations" within wider networks and forums, particularly during partners' attendance at high-profile events, such as the GHGT conference series.

Twitter: an example

The number of followers increased steadily over three years to 456 followers. These included NGOs, policymakers, research institutes and agencies, individual researchers, industry and other companies, media outlets and EU and other CCUS projects. The Twitter channel averaged between 4000 and 5000 impressions (the number of times a tweet is seen) each month, with spikes in interest relating to specific activities. For example, in August 2018, two web features (*Expert interview: Could legal issues prevent North sea oil & gas infrastructure being reused for CO_2 storage?* and *BLOG: Why do public responses to CCUS matter if CO_2 is stored offshore?*) resulted in a total of 15,300 tweet impressions.

ALIGNwiki

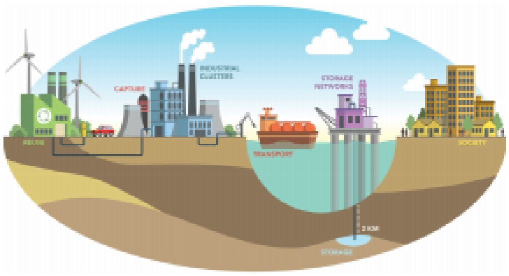
The ALIGNwiki site – https://wiki.alignccus.eu/ – developed by TNO, was launched in March 2020, providing user-friendly access to project objectives and outputs for a non-expert audience. The Wiki helped to deliver one of the key objectives of project C&D, that is, to disseminate findings and explain CCUS in engaging ways that allow the public to understand and assess their broader significance.

Project briefing

Produced at the start of the project, this full-colour, double-sided brochure provided a summary of the project's objectives and research focus, with details about each of the regions being studied. The document could be printed or used in PDF format and proved useful for partners attending conferences and other events, to help them quickly explain and promote the project and their role. It also served as a point of reference.

ALIGN CCUS

www.alignccus.eu



The international ALIGN-CCUS project unites science and industry in the shared goal of transforming Europe's industrial regions into economically robust, low-carbon centres by 2025.

Our partnership of 31 research institutes and industrial companies from five countries has secured European and national funding for carrying out interlinking areas of research into capturing, utilising and permanently storing carbon dioxide (CO_2).

By exploring specific issues faced by industry, we aim to support the quick and cost-effective deployment of carbon capture, utilisation and storage (CCUS), enabling Europe's industrial and power sectors to become part of a low-carbon future while remaining economically viable.

Our three-year project, which draws on considerable expertise from the project's partners, will focus on:

- Optimising and reducing the costs of CO_2 capture technology
- Planning large-scale CO_2 transport
- Providing sufficient and safe offshore CO_2 storage
- Developing the use of CO_2 in energy storage and conversion
- Supporting the social acceptance of CCUS

The project's technical research will make use of existing pilot and demonstration projects, which are in various phases of development. It will also focus on real-life industrial clusters, where companies have already identified CCUS as a key technology for reducing the environmental footprint of their operations.

A low-carbon transformation

The combined results of our research will be used to provide five industrial regions in Europe with blueprints to support and accelerate the delivery of low-emission industry clusters through CO_2 geological storage and CO_2 utilisation.

The project will also provide a portfolio of storage options for each cluster, along with advice on securing storage permits and planning future capacity.

North Rhine-Westphalia, Germany

Germany's most populated state is a focal point for industry and energy production, including many manufacturing industries and lignite-fired power plants. We will evaluate carbon capture and utilisation as a means of tackling CO_2 emissions across the region.

Oltenia, Romania

The blueprint for this region will identify the most feasible CO_2 transport routes for future captured CO_2 from Oltenia's industrial cluster, and will investigate suitable storage options, including the use of CO_2 in enhanced oil recovery.

Rotterdam, the Netherlands

Rotterdam Port has five large refineries, production plants for hydrogen, industrial gases and chemicals, fossil fuel power generation and waste incineration. Our research will support plans for a "hub" for decarbonising natural gas together with offshore CO_2 storage.

Grangemouth, United Kingdom

The focus of this cluster is a refinery complex for chemical products and Scotland's only crude oil refinery. It is the proposed site for Summit Power's Caledonia Clean Energy Project. We will identify possible cost reductions through shared infrastructure and optimised CO_2 transport and storage.

Grenland, Norway

Norcem's cement plant and Yara's ammonia plant are the region's largest CO_2 sources. Together with EGE's waste incineration plant in Oslo, they have been identified as ideal for CCUS. Our project will provide plans for an CO_2 surface storage facility.

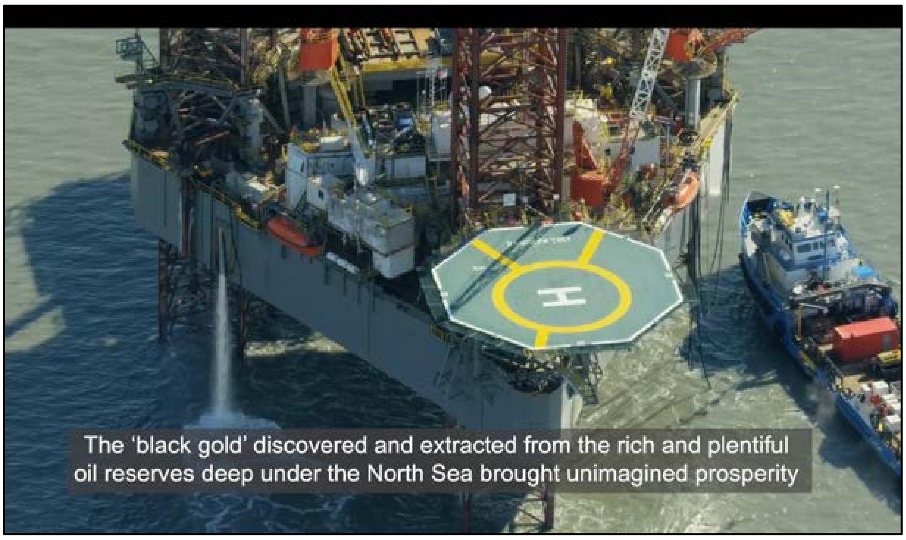
Teesside, United Kingdom

The Tees Valley is one of the UK's most densely clustered sites of manufacturing industries. Future plans include "clean hydrogen" production using CO_2 capture and storage. Our project will build on previous studies to identify cost reductions through shared transport and storage infrastructure.

info@alignccus.eu

Download here: https://www.alignccus.eu/sites/default/files/Align-Leaflet-v3.pdf

Videos



A range of videos has been produced by the WP0 team and other project partners. These include behind-the scenes visits to research facilities, a public engagement video on CO_2 storage and a time-lapse video of RWE Niederaussem's synthesiser unit taking shape. There is also a set of interviews with partners and other experts at the GHGT-15 conference. The final dissemination event in October 2020 featured short videos showcasing the work of researchers in each work package (see *Final dissemination*, below). The event kicked off with the first of two films, *How industry responds to climate change, and the role of CCS - An introduction*, produced for WP6 by the film company MediaVoodoo. The powerful narratives and imagery of these films have a relevance and use well beyond the conclusion of ALIGN-CCUS.
All videos can be found on the project's YouTube channel:
https://www.youtube.com/channel/UCEKgcIdb7UghBJzlWl8Sadg/videos

Webinars
A total of seven knowledge exchange webinars have been held, chaired by project coordinator Peter van Os and delivered by SCCS with the involvement of each work package team. The webinars, which had good registration and attendance, featured WPs 1, 2, 3, 4 and 6 plus an additional pre-recorded talk on offshore infrastructure reuse options. Post-event surveys have yielded good reviews. Webinars have been recorded so, in addition to around 400 stakeholders joining the live events, more than 300 people have watched afterwards. Live polls and live Q&A panels ensured audience participation. All webinar recordings, programmes and presenter details can be found on the Events feed: http://alignccus.eu/events

Workshops, presentations & papers
ALIGN-CCUS researchers have taken part in and co-organised a variety of conferences, workshops and online events. They have delivered around 70 oral presentations and 20 posters, and written more than 50 papers (published or in preparation). There is a full list of these activities, including descriptions and events further in the report.

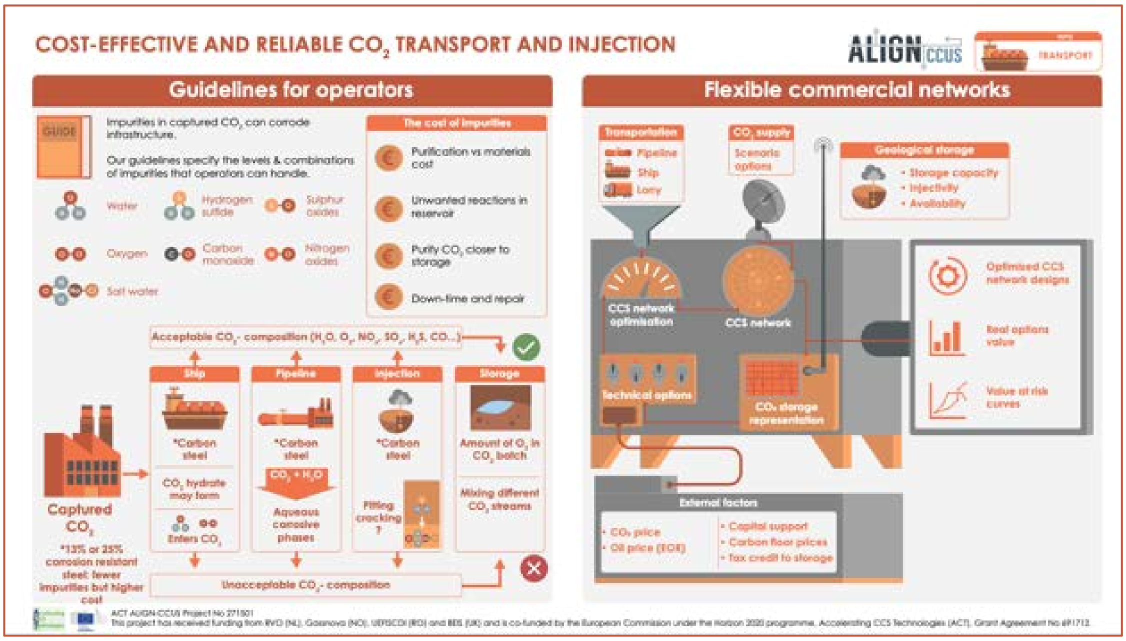
Final dissemination event
Work package completion dates were pushed back due to the Covid-19 crisis and associated lockdowns across Europe. As a result, the final knowledge sharing event, *CCUS ALIGNED Equipping industry for low-carbon success*, scheduled for July was held during two half-day online sessions on 28-29 October 2020. This was a very successful event and the learning from this experience will be of value to future projects. Full programme, materials and recordings: http://alignccus.eu/events/ccus-aligned-equipping-industry-low-carbon-success

The online event, delivered using the Zoom platform, used a novel format featuring:

- short "insight" videos of work package researchers and their focus;
- live presentations of project results by WP leads, using specially developed project infographics;
- Q&A sessions;
- *Meet the Experts* sessions for each WP allowing a deep dive into results, discussion among WP team members and an extensive Q&A with webinar attendees.

Day One was aimed at non-technical stakeholders while Day Two was more suited to an expert audience. Collectively, the event attracted representatives from industry and business (including oil and gas sector, manufacturing and refineries), regional large-scale CCUS projects, government departments and agencies, including funders, academia and research agencies, and CCUS consultancies.

Project infographics



Ahead of the final event, a graphic designer was commissioned to create a set of infographics, one for each work package. These comprised up to four individual infographics per work package, which could be displayed as a single poster or as individual infographics, for example, for PowerPoint presentations. The aim was to summarise the main research findings in a clear and appealing way, accessible to non-specialist audiences. Given the nature of the research, the infographic format was valuable in that maps, diagrams and other graphics could be combined with text, thereby explaining the findings more fully and with greater impact.

They proved a useful tool: the outputs were used during the presentations at the final event, on the project website and in social media. The process of creating them was also valuable in helping researchers distil their findings – highlighting the key messages and outcomes – and prepare for their public presentations. The full set of project infographics can be found in the appendix.

Dissemination and scientific conferences and events

Members of ALIGN-CCUS have been actively disseminating at scientific conference across the world, in addition to relevant events and webinars. A record of dissemination activities has been made and can be seen below (more than 145 instances).

ALIGN-CCUS dissemination activities since project start

What	Where	When	Who	Description
O	GCCSI CCS Hubs and Clusters Forum, Rotterdam, Netherlands	26-10-2017	BGS	ALIGN-CCUS project table, dissemination and project flyers
PR	Forschungsnetzwerk Energie Working Group 2 CO_2-Technologies of the German Federal Ministry of Economic Affairs and Energyz, Berlin	08-11-2017	RWE	Facts about the ALIGN-CCUS project, main focus on work in WP4.
O	CATO, Utrecht, Netherlands	23-11-2017	TNO	General ALIGN-CCUS presentation at CATO day
Web		30-11-2017	PMT	Accelerating low-carbon industrial growth through CCUS
PR		1-12-2017	ALIGN-CCUS	NL, NO, UK, DE, RO
O	CSLF, Abu Dhabi, United Arab Emirates	3-12-2017	GeoEcomar	General ALIGN-CCUS presentation
O	EERA-CCS, Brussels Belgium	14-12-2017	TNO	General ALIGN-CCUS presentation
O	ZEP, Brussels, Belgium	22-2-2018	TNO	General ALIGN-CCUS presentation
Po	UK CCS RC conference, Cambridge, UK	26-03-2018	BGS	ALIGN-CCUS project and collaboration between UK ERA-Net ACT projects
Po	UK CCS RC conference, Cambridge, UK	26-3-2018	UEDIN	The role of ‘place attachment’ in CCUS acceptance
I		28-3-2018	FZ Julich	ALIGN-CCUS innovation: can methanol-based synthetic fuels drive an energy revolution?
O	All Energy, Glasgow	02-05-2018	BGS	ERA-Net ACT projects and ALIGN-CCUS Accelerating Low-Carbon Growth through CCUS
B		14-5-2018	BGS	Pooling European learning and expertise to protect our atmosphere
Web		5-6-2018	WP4 Team	CCUS as an element for large-scale energy storage and conversion
O	IEAGHG Newsletter	13-06-2018	WP4 Team	News about WP4-Webinar
V	University of Sheffield, United Kingdom	26-6-2018	NCCS at PACT	Preparing for large scale CO_2 Capture – ALIGN-CCUS at the University of Sheffield.

What	Where	When	Who	Description
WS	Den Bosch, The Netherlands	28-6-2018	LU and TNO	Participation in the 'National Environmental Manager day' in Den Bosch, The Netherlands by LU and TNO to identify relevant practices, issues and stakeholders.
Pa	Newsletter GEO Energy	1-7-2018	ALIGN-CCUS	General information on ACT program
O	IAPS 2018, Rome, Italy	11-7-2018	LU	Great green bribe or good practice? Community compensation in the context of Carbon Capture and Storage
B		15-8-2018	LU	Why do public responses to CCUS matter if CO_2 is stored offshore? (Blog republished in/shared via the CATO newsletter, the Leiden University newsletter)
I		29-8-2018	RUG	Expert interview: Could legal issues prevent North Sea oil & gas infrastructure being reused for CO_2 storage?
O	BEHAVE 2018, Zurich, Switzerland	7-9-2018	LU	Public debate on carbon capture and storage: statements and visual frames used in Dutch newspapers
I	Leiden University website/newsletter	18-9-2018	LU	Expert interview: Psychologists test societal acceptance of underground CO_2 (republished in Carbon Capture Journal)
O	Forschungsnetzwerk Energie Working Group 2 CO_2-Technologies of the German Federal Ministry of Economic Affairs and Energy, Darmstadt	18-9-2018	RWE	Internationale CCS/CCUS-Tätigkeiten „Mission Innovation“ und SET-Plan and Status ALIGN-CCUS
Pat	Patent application	24-9-2018	RWE	Verfahren zum Betrieb eines Kraftwerkes zur Erzeugung von elektrischer Energie durch Verbrennung eines kohlenstoffabhängigen Brennstoffs und entsprechendes System zum Betreiben eines Kraftwerkes
Pa		1-10-2018	LU	Why do public responses to CCUS matter if CO_2 is stored offshore? Carbon Capture Journal - Issue 65
WS	Rotterdam, NL	13-10-2018	LU	ALIGN-CCUS WP6 participation in ACORN Just transition workshop
Pa	For UK CCS Association, London, response to CCUS Cost Challenge Taskforce recommendations	15-10-2018	BGS	Re-use of North Sea infrastructure for CO_2 storage

What	Where	When	Who	Description
Pa	For UK CCS Association, London, response to CCUS Cost Challenge Taskforce recommendations	15-10-2018	BGS	A framework to demonstrate progress in storage site development: CO_2 storage site readiness criteria
OPa	KWTK 2018, Dresden, Germany	24-10-2018	RWE, MHPSE, AKAE, FZ Julich, RWTH, FEV	Synthese des Dieselersatztreibstoffs DME aus abgetrenntem CO_2 des Kraftwerks Niederaußem – Demonstration der gesamten CCU-Kette und Sektorkopplungmany
Po	GHGT14, Melbourne, Australia	25-10-2018	TNO, SINTEF IND, BGS, RWE, LU	ALIGN-CCUS: an ERA ACT project on the full CCUS chain to accelerate implementation of decarbonisation in industrial areas
OPa	GHGT14, Melbourne, Australia	25-10-2018	BGS, SINTEF IND, TNO	Steps to achieve storage readiness for European industrial CO_2 source clusters, ALIGN-CCUS
OPa	GHGT14, Melbourne, Australia	25-10-2018	TNO, TAQA	Initiating large-scale storage in the Netherlands offshore
OPa	GHGT14, Melbourne, Australia	25-10-2018	TNO, BGS, SINTEF IND, FZ Julich, GeoEcomar, Bellona	Targeted CCUS R&D activities in industrial clusters
OPa	GHGT14, Melbourne, Australia	25-10-2018	TNO	De-oxygenation as countermeasure for the reduction of oxidative degradation of CO_2 capture solvents
PoPa	GHGT14, Melbourne, Australia	25-10-2018	TNO	Lab scale investigation on the formation of aerosol nuclei by a Wet Electrostatic Precipitator in the presence of SO2 in a gas stream
OPa	GHGT14, Melbourne, Australia	25-10-2018	TNO	In-situ experimental investigation on the growth of aerosols along the absorption column in PCCC
PoPa	GHGT14, Melbourne, Australia	25-10-2018	HWU, TNO, RWE	Impact of transient operation on amine emissions at the Niederaussem capture plant.
OPa	GHGT14, Melbourne, Australia	25-10-2018	RWE, MHPSE, AKAE, FZ Julich, RWTH, FEV, TNO	Demonstrating the CCU-Chain and Sector Coupling as Part of ALIGN-CCUS - Dimethylether from CO_2 as chemical Energy Storage, Fuel and Feedstock for Industries
PoPa	GHGT14, Melbourne, Australia	25-10-2018	RWE, TNO, USN, HWU, SINTEF IND	MEA consumption – ALIGN-CCUS: Comparative long-term testing to answer the open questions

What	Where	When	Who	Description
PoPa	GHGT14, Melbourne, Australia	25-10-2018	NTNU, SINTEF IND	Aerosol growth in an absorber for a post combustion CO_2 capture using the 2-Amino-2-methyl-1-propanol/ Piperazine (CESAR 1) solvent
OPa	GHGT14, Melbourne, Australia	25-10-2018	USN	Electrochemical Corrosion Measurements of MEA aqueous solutions at elevated temperatures
WS	GHGT14, Melbourne, Australia	26-10-2018	ALIGN-CCUS, CSIRO,	Knowledge exchange workshop ALIGN-CCUS
V	GHGT14, Melbourne, Australia	6-11-2018	BEIS	ALIGN-CCUS@GHGT-14 - interview with Brian Allison, BEIS
V	GHGT14, Melbourne, Australia	6-11-2018	CSIRO	ALIGN-CCUS@GHGT-14 - interview with Graeme Puxty, CSIRO
V	GHGT14, Melbourne, Australia	6-11-2018	TNO	ALIGN-CCUS@GHGT-14 - interview with Peter van Os, TNO
V	GHGT14, Melbourne, Australia	6-11-2018	TNO	ALIGN-CCUS@GHGT-14 - interview with Tom Mikunda, TNO
V	GHGT14, Melbourne, Australia	6-11-2018	BGS	ALIGN-CCUS@GHGT-14 - interview with Maxine Akhurst, British Geological Survey
B		23-11-2018	TNO	Coincidence or just excellent planning?
Po	Accelerating CCUS: A Global Conference to Progress CCUS' IEA/BEIS. International ministerial conference, Edinburgh, UK	28-11-2018	BGS	ALIGN-CCUS project
V		28-11-2018	BGS	Storing CO_2 in the subsurface
WS	ENOS workshop, Oostvoorne, NL	13-12-2019	LU	LU expert contribution in ENOS data collection workshop
O	Annual Norwegian CO2 conference arranged by TEKNA	16-01-2019	SINTEF	"Karbon fangst, transport og lagring fra industriklynger", Carbon capture, transport and storage from industrial clusters
O	Forschungsnetzwerk Energie Working Group 2 CO_2-Technologies of the German Federal Ministry of Economic Affairs and Energy, Essen	12-02-2019	RWE	Presentation about „Status of ALIGN-CCUS“
Web		13-2-2019	WP2 Team	Preparing for large-scale transport for offshore CO_2 storage
Po	Decarbonisation and Resource Management workshop, BGS Keyworth, UK	21-02-2018	BGS	ALIGN-CCUS project
I	Leiden University website	15-03-2019	LU	Expert interview: Public perception of energy projects
A	ICEP, Plymouth, UK	01-04-2019	LU, ECN part of TNO	The importance of community engagement for underground CO_2 storage: Lessons and insights from the field

What	Where	When	Who	Description
WS	BGS, Edinburgh, UK	9-4-2019	RUG, BGS	Legal issues stakeholder workshop on infrastructure reuse in the UK
O	CCUS leadership group, Scottish Government	25-4-2019	BGS, SCCS, Scot Ent	Presentation of progress on storage and UK case study to Scottish Government representatives
OPo	All Energy conference, Glasgow, UK	15-5-2019	BGS, SCCS, Scot Ent	Conference presentation of ALIGN-CCUS Storage Readiness Levels, ALIGN-CCUS project poster and panellist at CCUS session
O	12th Meeting of the expert group "Power-to-Gas" of the Energy Agency North-Rhine-Westphalia	27-05-2019	RWE, FZ Julich, AKEU	Presentation about status of ALIGN-CCUS and the work in WP4
WS	BGS, Edinburgh, UK	12-6-2019	BGS, SDL, Scot Ent	Business case stakeholder meetings with INEOS, Scottish Government, Scottish Hydrogen & Fuel Cell Association, Scottish Enterprise
WS	Scottish Gas Network	12-6-2019	BGS, SDL	Business case stakeholder meetings with Scottish Gas Networks
Web	ENOS webinar	June 2019	LU	ALIGN-CCUS WP6 contribution (presentation + discussion) to ENOS webinar
OPa	TCCS10, Trondheim, Norway	19-6-2019	LU	Is public debate around carbon capture and storage changing? Exploring statements and visual frames used in Dutch newspapers
Opa	TCCS10, Trondheim, Norway	19-6-2019	TNO	De-oxygenation as countermeasure for the reduction of oxidative degradation of CO_2 capture solvents
OPa	TCCS10, Trondheim, Norway	19-6-2019	TNO	Network design and flexibility for low-pressure depleted gas reservoirs: hot or cold CO_2?
OPa	TCCS10, Trondheim, Norway	19-6-2019	TNO	Planning CO_2 transport and storage infrastructure in the Netherlands offshore
OPa	TCCS10, Trondheim, Norway	19-6-2019	USN	Corrosivity of degraded MEA solvent and fresh solvent added organic acids and salts
Po	TCCS10, Trondheim, Norway	19-6-2019	USN	Corrosivity of MEA solvent at stripper conditions
Po	TCCS10, Trondheim, Norway	19-6-2019	IFE	Review of CO_2 specifications and experimental data used for verification
OPa	TCCS10, Trondheim, Norway	19-6-2019	SINTEF	Storage resources for future European CCS deployment; A roadmap for a Horda CO_2 Storage Hub, offshore Norway

What	Where	When	Who	Description
A	ICCDU2019, Aachen, Ger	25-6-2019	FZ Julich, RWE, MHPSE, AKAE, RWTH, TNO	Life Cycle Assessment of CCU-Chain Demonstration in the ALIGN-CCUS project – Dimethyl Ether and Oxymethylen Ether from CO_2
WS	Spijkenisse, The Netherlands	26-6-2019	LU	Workshop Public Perception at CATO event.
O	Energy and Climate Change seminar	June 2019	SNSPA	Participation/presentation by WP6 SNSPA team in the seminar.
WS/O	CATO event, Spijkenisse, the Netherlands	July 2019	LU, ECN part of TNO	Two workshops on public perception, community engagement and community compensation held at the CATO event.
WS	Leiden, the Netherlands	July 2019	LU, ECN part of TNO	6.2 stakeholder workshop on community engagement/compensation
B	ALIGN-CCUS newsletter item	July 2019	LU	Practising public engagement at North Sea CCUS event
WS		September	LU	Participation in ECOBASE meeting
O	UK CCS RC Programme Conference, Edinburgh, Scotland, UK	04-09-2019	BGS	ALIGN-CCUS - Accelerating Low-carbon Industrial Growth through CCUS
OPa	VGB KONGRESS 2019 – Innovation in Power Generartion, Salzburg, Austria	05-09-2019	RWE, MHPSE, FZ Julich, AKEU, FEV, RWTH	The project ALIGN-CCUS - A contribution to the evolutionary transformation process of energy and raw material supply through recycling of carbon
O	EU CCS Storage Research Projects Science-Policy Showcase, Brussels, Belgium	10-09-2019	BGS	Permanent geological storage of CO_2 captured at a UK industrial cluster: present day to 2100
A	PCCC-5, Kyoto, Japan	18-9-2019	HWU, RWE, TNO	Analysis of flexible operation of CO_2 capture plants: Predicting Solvent Emissions from conventional and advanced amine systems
A	PCCC-5, Kyoto, Japan	18-9-2019	RWE, TNO, HWU	ALIGN-CCUS: Results of the 18-month test with MEA at the pilot plant at Niederaussem – solvent management, emissions and dynamic behavior
A	PCCC-5, Kyoto, Japan	18-9-2019	SINTEF IND	Dynamic model development in ALIGN-CCUS
OPa	Qualitative Research in Communication International Conference, Bucharest, Romania	25-9-2019	SNSPA	Paper presentation 'Adapting a cross-country methodology to investigate local CCUS stakeholder communities'
OPa	Qualitative Research in Communication International Conference, Bucharest, Romania	25-9-2019	SNSPA	Paper presentation 'Challenges and success factors of CCUS implementation: A stakeholder approach/perception review'

What	Where	When	Who	Description
Ws	ECO-BASE workshop, Bucharest	September 2019	SNSPA	Participation/presentation by SNSPA (WP6) in ECO-Base workshop
Opa	ICEP, Plymouth, UK	September 2019	LU, ECN part of TNO	The importance of community engagement for underground CO_2 storage: Lessons and insights from the field
O	STEMM-CCS Storage Research Showcase, Brussels, Belgium	10-9-2019	BGS	Presentation of ALIGN-CCUS WP3 for UK case study to industry, researchers and EC stakeholders
O	Lyell Centre GeoEnergy Symposium, Edinburgh, UK	2-10-2019	BGS	Presentation of ALIGN-CCUS WP3 for UK case study to industry and researchers.
O	UK CCS RC conference, Edinburgh, UK	4-10-2019	BGS	Presentation of ALIGN-CCUS WP3 for UK case study to industry and researchers.
O	PreAct project stakeholder meeting, Brussels, Belgium	10-10-2019	BGS, SINTEF, TNO	Presentations summarising ALIGN-CCUS and WP3 for UK case study, transport and storage networks for The Netherlands and Norway, to industry, research and EC stakeholders
Opa	CSM2019, Catania, Italy	15-10-2019	RWTH, FEV	Optical spray investigations on OME3-5 in a constant volume high pressure chamber.
Opa	KWTK 2019, Dresden, Germany	22-23 October 2019	MHPSE, RWE, FZ Jülich	"ALIGN-CCUS: Synthese des Dieselersatztreibstoffs DME aus abgetrenntem CO_2 des Kraftwerks Niederaussem – Demonstration der gesamten CCU-Kette"
Web	ALIGN-CCUS Webinar 5	30-10-2019	BGS, SCCS, TNO, SINTEF	Development of CO2 storage networks for industrial clusters: storage readiness; infrastructure re-use & network development NL; development of a Horda Platform storage hub NO.
O	CCS Knowledge Session, The Hague, The Netherlands	31-10-2019	LU	Oral presentation on societal perception and acceptance of CCS--focus on relevance of social science research, relevant research projects and lessons learned.
Pa	Paper published for publication in International Journal of Greenhouse Gas Control https://authors.elsevier.com/sd/article/S1750-5836(20)30553-3	1-11-2019	LU, UEDIN, ECN part of TNO, JUELICH, SNSPA	Task 6.2.1 research/review paper "Community compensation in the context of Carbon Capture and Storage: Key debates and current practices" is published
A	KLI conference, Zeist, the Netherlands April 2020	11-11-2019	LU	Abstract submitted for oral presentation at the 2020 KLI conference: "Understanding public opposition to infrastructure and energy projects: The role of trust and fairness"

What	Where	When	Who	Description
O	RWE, Germany, Inauguration ceremony at Niederaussem	21-11-2019	RWE, TNO	In the course of the inauguration ceremony at Niederaussem for the demonstrator (WP4): „Neue Anlage erzeugt emissionsarmen Diesel-Ersatztreibstoff.“
PR	Coupled to the ALIGN-CCUS meeting in Niederaussem (November 2019)	24-11-2019	RWE	Commissioning of the ALIGN-CCUS demonstration plant has started - Diesel substitute DME from CO2, water and electricity
O	Oil and Gas Authority, London, UK	25-11-2019	BGS	BGS activities in supporting CCUS and infrastructure re-use
O	Climate Change Committee, London, UK	25-11-2019	BGS	Update of emerging findings of UK case study, ALIGN-CCUS project
O	Invited keynote presentation given at Scottish Alliance Geoscience Environment and Society conference, Edinburgh	26-11-2019	BGS	ALIGN-CCUS project and UK case study emerging findings, an invited keynote presentation given at Scottish Alliance Geoscience Environment and Society conference, Edinburgh, 26 November 2019.
O	SAGES conference: Global Climate Challenges for a Blue Green Economy, Edinburgh, UK	27-11-2019	BGS	Reducing atmospheric CO_2 emissions from industrial sources, domestic and commercial heating in Scotland
Pa	Paper submitted for publication in VGB PowerTech	15-1-2020	RWE, MHPSE, AKEU, FZ Jülich, RWTH, FEV	Das Projekt ALIGN-CCUS – Ein Beitrag zum evolutiven Transformationsprozess der Energie- und Rohstoffversorgung durch Recycling von Kohlenstoff
O	UTCCS-5	29.01.2020	RWE, TNO	Results on solvent degradation and management from long-term testing of MEA and aqueous AMP/PZ solvent at the Niederaussem pilot plant
A	IEAGHG Newsletter	6-3-2020	WP4	Report about WP4 inauguration ceremony at Niederaussem
I	Interview Peter van Os TKI Gas	March 2020	TNO	ALIGN-CCUS: Naar een koolstofarme Europese industrie
I	Leiden University website/newsletter	30 March 2020	LU	Interview held with Emma ter Mors (LU), WP6 leader
Web	ALIGN-CCUS WP6 webinar	31 March 2020	LU, TNO, SNSPA, SNSPA	ALIGN-CCUS WP6 webinar
Pa	Journal of Greenhouse Gas Control	1-4-2020	RWE, TNO, HWU	Results on 18-months MEA test at Niederaussem
Web	Re-invent webinar	May 2020	TNO	WP6 contribution to Re-Invent webinar (Task 6.1 and Task 6.2 research findings)
I	German federal report energy science	1-6-2020	RWE	Report about WP4 activities at Niederaussem
Web	ALIGN-CCUS WP1 webinar	25-06-2020	SINTEF, TNO, RWE, HWU	Preliminary results from WP1 presented by WP1 leader and Task-leaders of WP1.

What	Where	When	Who	Description
I, V	Online-Portal Industrial Research», BMWi	1-7-2020	RWE	Video about WP1 and WP4 activities at Niederaussem
Pa	International Journal of Greenhouse Control	July 2020	LU, UEDIN, TNO, SNSPA, FZ Julich	Task 6.2 paper published in International Journal of Greenhouse Gas Control: Community compensation in the context of Carbon Capture and Storage: Current debates and practices.
Pa	Submitted to International Journal of Greenhouse Gas Control	August 2020	NTNU, SINTEF	Aerosol growth in absorption columns, modelling and comparison with experimental results
I	Interview Peter van Os for ENDS Europe	24-8-2020	TNO	Importance of ALIGN-CCUS for carbon mitigation
OPa	KWTK 20, Dresden, Germany	07-10-2020	Mitsubishi Power, RWE, FZ Julich	ALIGN-CCUS: Synthese und Nutzung des Dieselersatztreibstoffs DME aus abgetrenntem CO2 – Ergebnisse der gesamten CCU-Kette am Standort Niederaußem
Pa	Paper in preparation	17-10-2020	NTNU	Solubility of CO2 in 0.1M, 1M and 3M of 2-Amino-2-methyl-1-propanol (AMP) from 313 to 393K and model representation using the eNRTL framework
Pa	Paper in preparation	17-10-2020	SINTEF IND	Storage resources for future European CCS deployment; a roadmap for a Horda CO2 Storage Hub, offshore Norway
V	SINTEF, Trondheim, Norway	28-10-2020	SINTEF	Tiller pilot plant
V	RWE, Germany	28-10-2020	Movie by SCCS at RWE	WP1 and WP4
O	SDE++ meeting in The Hague, The Netherlands	31 October 2010	LU	Public perception of CCS presentation held by LU (WP6)
Pa	Energy Research & Social Science	December 2020	TNO, UEDIN, LU	Task 6.1 paper submitted for publication in ERSS: Public opinion of industrial CCS in the UK and the Netherlands: Effects of outcome perceptions, proximity and industry attitudes
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	HWU, SINTEF, TNO	Process integration of advanced amine-based solvents in power and industrial plants: A new benchmark for post-combustion carbon capture
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	HWU, RWE, TNO	Analysis of flexible operation of CO2 capture plants: Predicting solvent emissions from conventional and advanced amine systems

What	Where	When	Who	Description
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	TNO, SINTEF, BGS, RWE, LU	ALIGN-CCUS: Results of the ERA-ACT project on the full CCUS chain to accelerate implementation of decarbonisation in industrial areas
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	TNO, NTNU, SINTEF	Impact of Dissolved Oxygen Removal on Solvent Degradation for Post-Combustion CO2 Capture
OPa	GHGT-15 – online conference	15-18 March 2020	NTNU, SINTEF	Aerosol Growth in a Post Combustion CO2 Capture Absorber Using the 2-Amino-2-Methyl-1-Propanol/Piperazine (CESAR 1) Solvent
OPa,	GHGT-15 – online conference	15-18 March 2020	TCM	First Process Results and Operational Experience with CESAR1 Solvent at TCM with High Capture Rates (ALIGN-CCUS Project)
OPa,	GHGT-15 – online conference	15-18 March 2020	TCM	Atmospheric emissions of amino-methyl-propanol, piperazine and their degradation products during the 2019-20 ALIGN-CCUS campaign at the Technology Centre Mongstad
OPa,	GHGT-15 – online conference	15-18 March 2020	TCM	CO2 Capture and work environmental sampling lessons learned
PoPa	GHGT-15 – online conference	15-18 March 2020	TCM	Best practices for the measurement of 2-amino-2-methyl-1-propanol, piperazine and their degradation products in amine plant emissions
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	BGS, TNO, SINTEF	Communicating site technical, permitting and planning readiness for CO_2 storage operations using the ALIGN-CCUS framework of storage readiness levels – Maxine Akhurst, Karen Kirk, Filip Neele, Alv-Arne Grimstad, Michelle Bentham, Per Bergmo
Opa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	ICL, TNO	CO_2 pipeline transport and storage network cost modelling and multi-period multi-scenario stochastic optimisation – Zhenggang Nie, Anna Korre, Sevket Durucan, Denis Fraga, Tom Mikunda, Filip Neele
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	RWE, TNO, HWU	ALIGN-CCUS: Results of the 18-month test with aqueous AMP/PZ solvent at the pilot plant at Niederaussem – solvent management, emissions and dynamic behavior

What	Where	When	Who	Description
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	RWE, MHPSE, AKEU, FZ Jülich, RWTH, FEV, TNO	ALIGN-CCUS: Production of dimethyl ether from CO2 and its use as an energy carrier - Results from the CCU demonstration plant
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	FZ Jülich, RWE	Life Cycle Assessment for full chain CCU demonstration in the ALIGN-CCUS project –dimethyl ether and polyoxymethylen dimethyl ethers production from CO2 and its usages in the mobility and electricity sectors
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	SINTEF IND	Design of a multi-user intermediate storage facility
OPa	GHGT15, Khalifa University, Abu Dhabi	15/18 March 2021	ICL	Multi-period cost optimisation of multi-mode carbon capture and storage chains.
OPa	52nd “Kraftwerkstechnisches Kolloquium” 2020 in Dresden, Germany	2020	RWE+ WP4 partners	General WP4 presentation/publication
PR	www.strom-forschung.de,BMWi/PtJ information platform	2020	RWE+ WP4 partners	Article and photo's
A	Information about ALIGN-CCUS was provided to the International Renewable Energy Agency (IRENA) and the Methanol Institute, which are preparing a publication.	2020	RWE+ WP4 partners	Publication will be prepared.

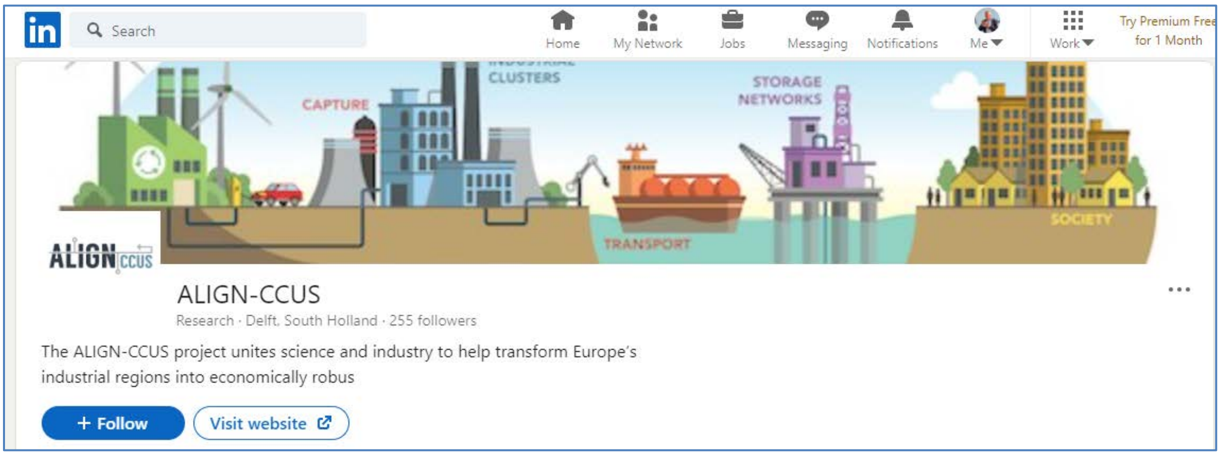
O = Oral Presentation, Web = Webinar, WS = WorkShop, V = Video, A = Abstract, B = Blog, I = Interview, Po = Poster, Pa = Paper, Pat= Patent application, OPa = Oral presentation and paper, PoPa = Poster and Paper, PR = Press Release

Social media attention

In addition to dissemination activities within the scientific community, ALIGN-CCUS has managed to create a significant social media presence to provide access to the project's activities to the general public.

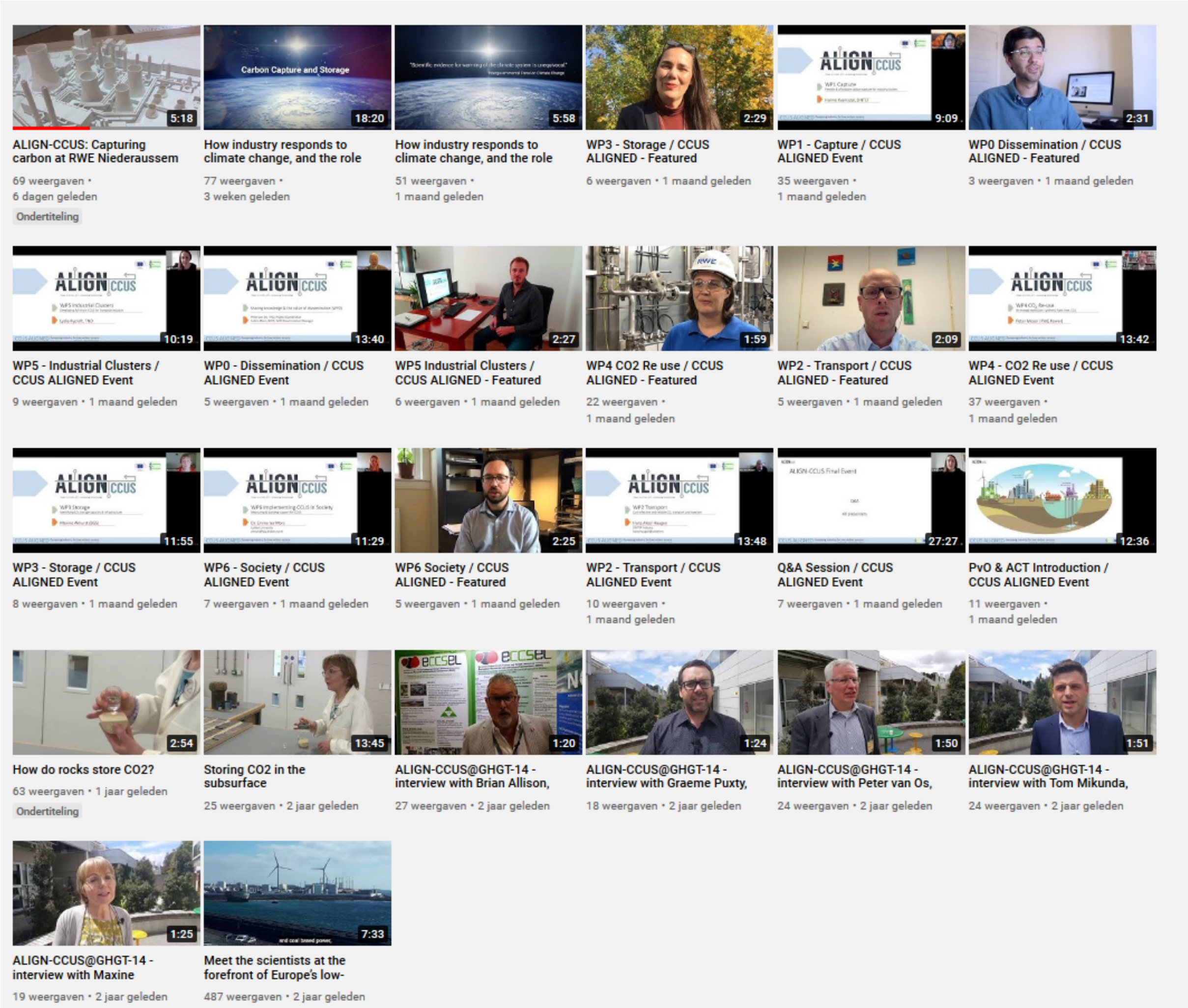
Twitter

LinkedIn



YouTube

Twenty-six videos have been published on Youtube with 1060 views registered in December 2020.12.24

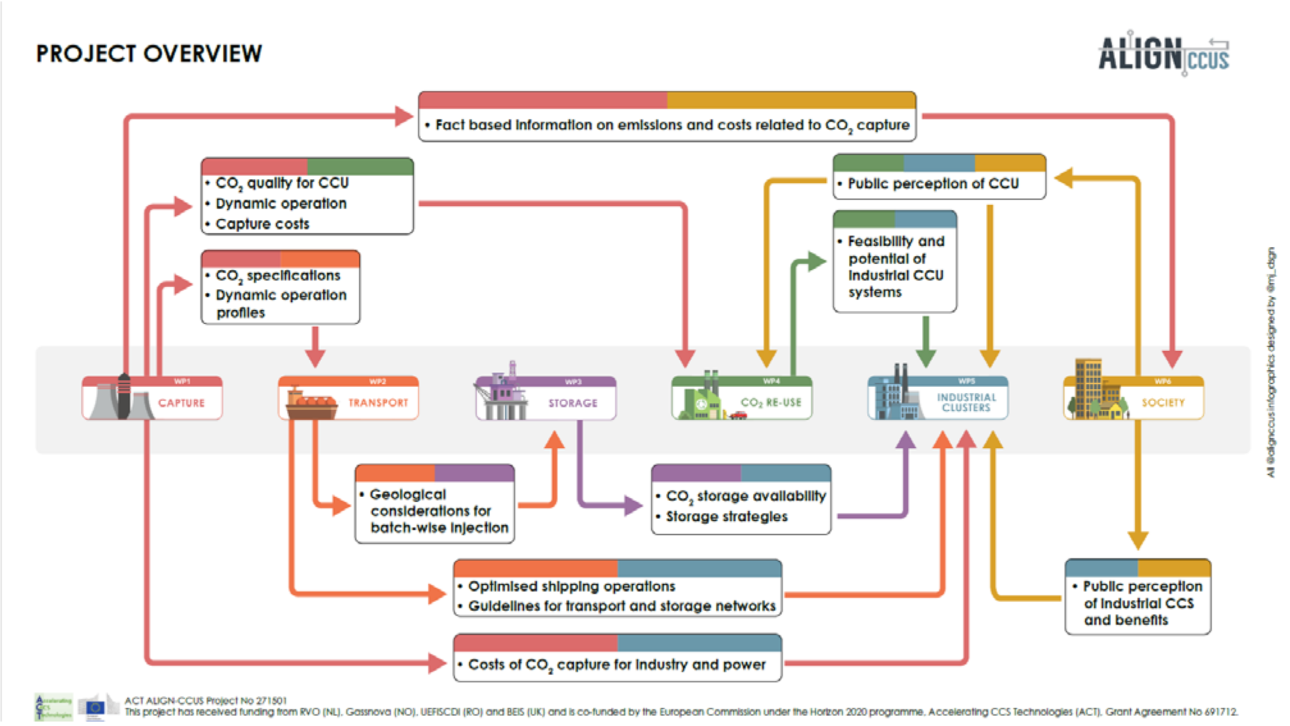


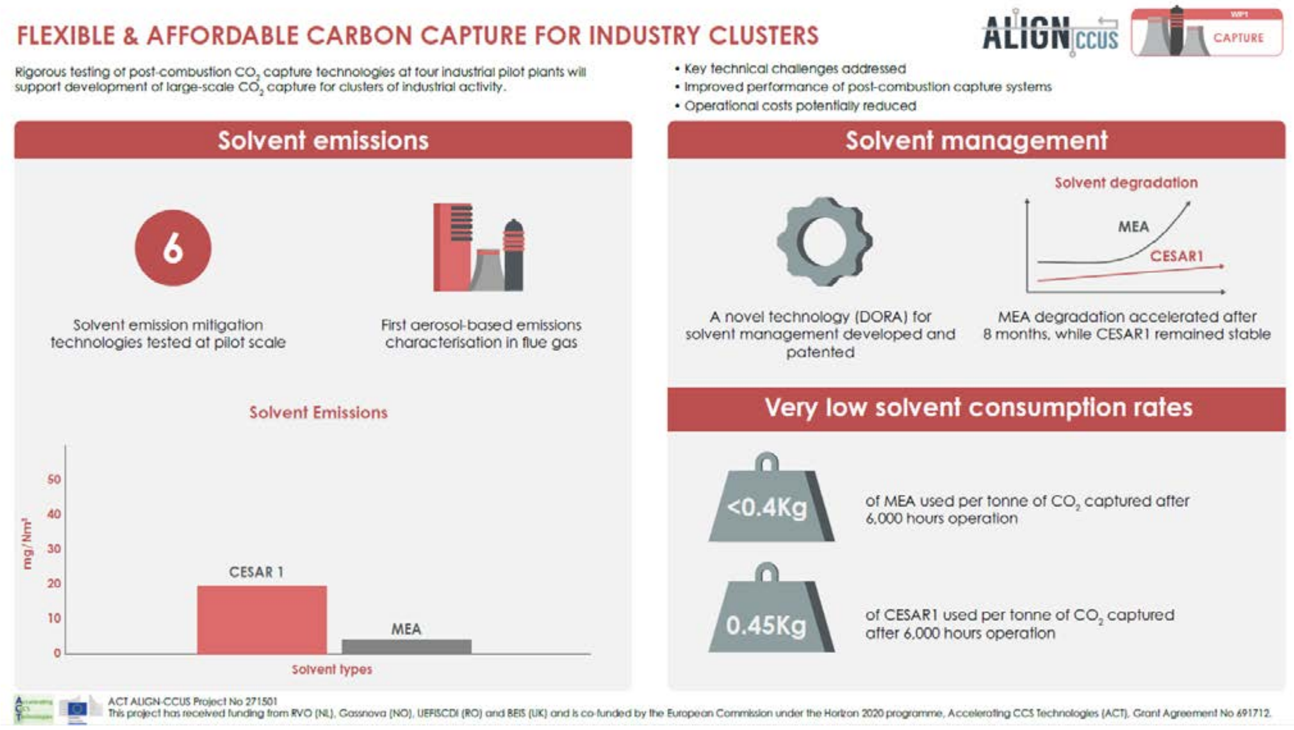
Sign:

Peter van Os, ALIGN-CCUS Coordinator

Date: January 10th 2021

APPENDIX ALIGN-CCUS Infographics.





FLEXIBLE & AFFORDABLE CARBON CAPTURE FOR INDUSTRY CLUSTERS

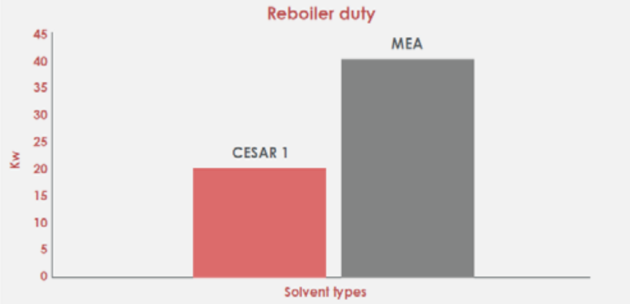
ALIGN CCUS — WP1 CAPTURE

Pilot plant operations

4 pilot plants

- RWE Niederaussem, Germany
- TCM and Tiller Lab, Norway
- PACT facilities, United Kingdom

12,000 hours of operation with MEA and CESAR1 (each) at RWE pilot plant

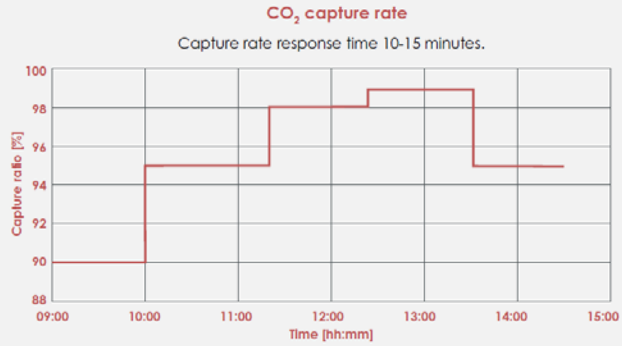


Process control

Successful demonstration of Advanced Non-linear Model Predictive Control (NMPC)

Low ***specific reboiler duty** during very large disturbances in CO_2 flow and CO_2 gas composition

***Reboiler duty** = total energy required for regeneration of solvent for reuse.



ACT ALIGN-CCUS Project No 271501
This project has received funding from RVO (NL), Gassnova (NO), UEFISCDI (RO) and BEIS (UK) and is co-funded by the European Commission under the Horizon 2020 programme, Accelerating CCS Technologies (ACT), Grant Agreement No 691712.

COST-EFFECTIVE AND RELIABLE CO_2 TRANSPORT AND INJECTION

ALIGN CCUS — WP2 TRANSPORT

Carbon capture and storage (CCS) requires flexible and affordable transport to carry varying amounts of captured CO_2 from source to geological storage or facilities that make products from CO_2.

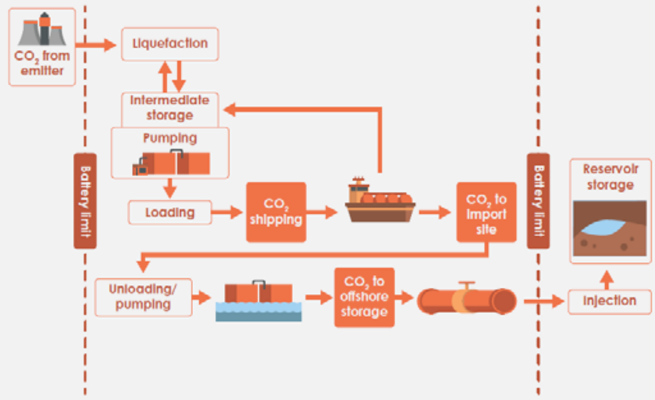
Our modelling studies show that a region-specific approach is the best route to providing effective transport and storage for industry clusters.

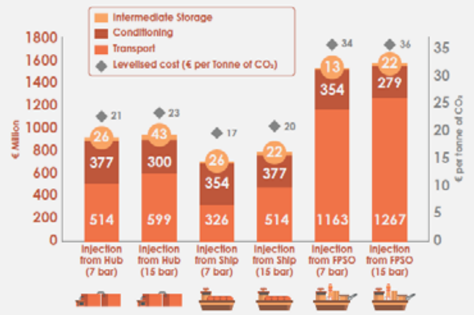
- Technical challenges of marine shipping and CO_2 offloading
- Maintaining storage site integrity when CO_2 is injected in batches
- Opportunities for cost reduction and enhanced safety

Results

- Bespoke planning tools for ALIGN-CCUS industry clusters
- Guidelines for flexible commercial transport & storage networks / 'Real options' decision frameworks for real-life application
- Guidelines on CO_2 composition for pipeline and ship transport
- Effect of batch-wise and cyclic CO_2 injection on storage site integrity

Planning a transport chain





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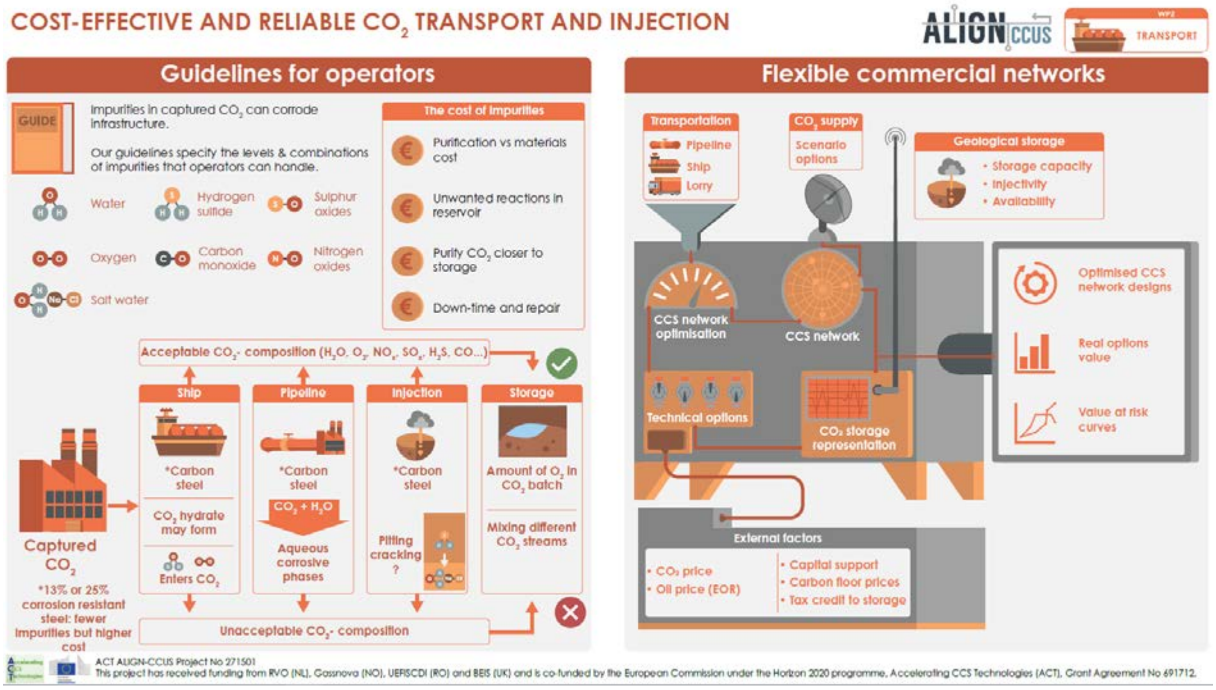
COST-EFFECTIVE AND RELIABLE CO2 TRANSPORT AND INJECTION
ALIGN CCUS
WP2
TRANSPORT
Guidelines for operators
GUIDE
Impurities in captured CO2 can corrode infrastructure.
Our guidelines specify the levels & combinations of impurities that operators can handle.
Water
Hydrogen sulfide
Sulphur oxides
Oxygen
Carbon monoxide
Nitrogen oxides
Salt water
The cost of impurities
Purification vs materials cost
Unwanted reactions in reservoir
Purify CO2 closer to storage
Down-time and repair
Acceptable CO2- composition (H2O, O2, NOx, SOx, H2S, CO...)
Ship
Pipeline
Injection
Storage
*Carbon steel
*Carbon steel
*Carbon steel
Amount of O2 in CO2 batch
CO2 hydrate may form
CO2 + H2O
Aqueous corrosive phases
Pitting cracking ?
Mixing different CO2 streams
Enters CO2
Captured CO2
*13% or 25% corrosion resistant steel: fewer impurities but higher cost
Unacceptable CO2- composition
Flexible commercial networks
Transportation
Pipeline
Ship
Lorry
CO2 supply
Scenario options
Geological storage
• Storage capacity
• Injectivity
• Availability
CCS network optimisation
CCS network
Technical options
CO2 storage representation
Optimised CCS network designs
Real options value
Value at risk curves
External factors
• CO2 price
• Oil price (EOR)
• Capital support
• Carbon floor prices
• Tax credit to storage
ACT ALIGN-CCUS Project No 271501
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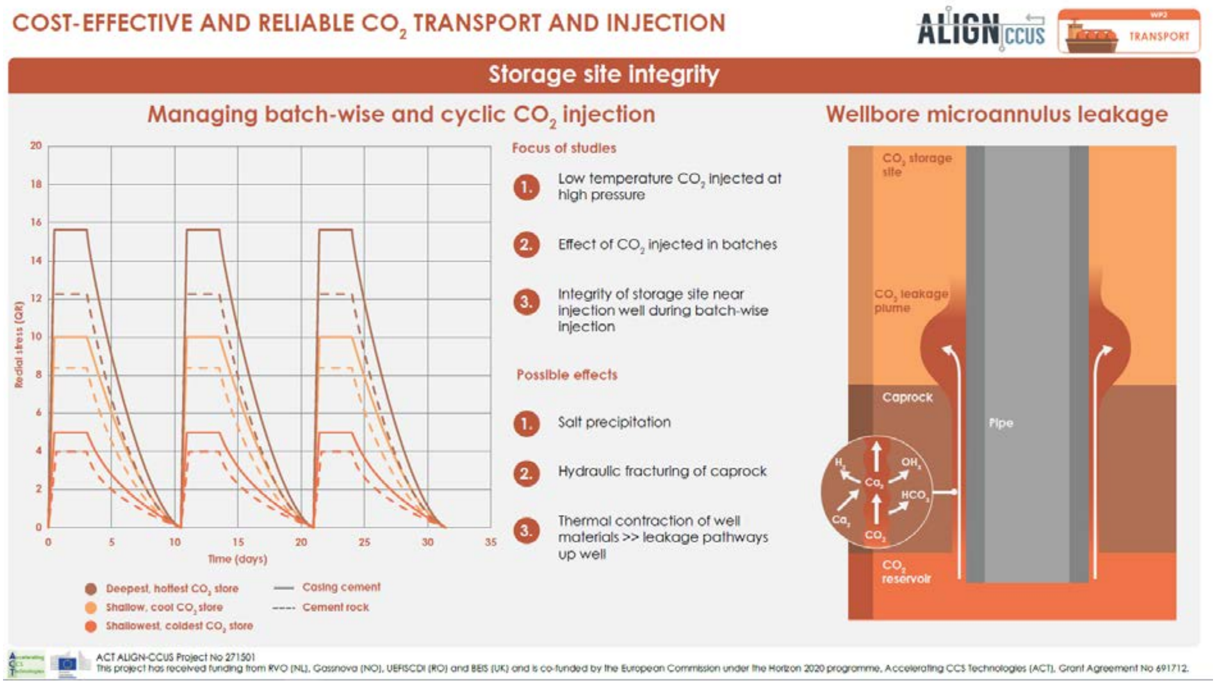
COST-EFFECTIVE AND RELIABLE CO2 TRANSPORT AND INJECTION
ALIGN CCUS
WP2
TRANSPORT
Storage site integrity
Managing batch-wise and cyclic CO2 injection
Radial stress (GPa)
Time (days)
Deepest, hottest CO2 store
Shallow, cool CO2 store
Shallowest, coldest CO2 store
Casing cement
Cement rock
Focus of studies
1. Low temperature CO2 injected at high pressure
2. Effect of CO2 injected in batches
3. Integrity of storage site near injection well during batch-wise injection
Possible effects
1. Salt precipitation
2. Hydraulic fracturing of caprock
3. Thermal contraction of well materials >> leakage pathways up well
Wellbore microannulus leakage
CO2 storage site
CO2 leakage plume
Caprock
Pipe
CO2 reservoir
ACT ALIGN-CCUS Project No 271501
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IDENTIFYING CO_2 STORAGE CAPACITY & INFRASTRUCTURE FOR RE-USE

Our research confirms matched CO_2 storage capacity in the North Sea for the ALIGN-CCUS industrial clusters and the steps needed to make sites operational and support large-scale CO_2 capture.

- Established options and potential timelines for CO_2 storage & transport network development
- Developed framework to show storage site readiness levels
- Applied and ranked published criteria for oil & gas infrastructure re-use

Infrastructure re-use

ALIGN-CCUS has ranked published criteria for oil & gas infrastructure re-use by testing their effectiveness and ease of application.

We then applied the criteria to the national storage portfolios.

1. Location of infrastructure relative to CO_2 sources
2. Timeline of availability
3. Remaining lifespan
4. Transport or weight capacity
5. Compatibility of materials with CO_2-rich environment
6. Integrity of existing wells
7. Materials used for wells

Right time, right place for re-use

We applied these re-use rankings to our study area.
Are sites & supporting infrastructure available when needed?

- O&G fields being depleted at present, in timeframe suitable for infrastructure conversion to CCS use e.g. Porthos Project (NL)
- Production ongoing. Limited possibilities for re-use of infrastructure for CCS in coming decades e.g. Troll Field (NO)
- Depleted O&G fields shut down and some infrastructure dismantled as feasible CCS projects did not materialise in time e.g. Miller (UK), Frigg (NO), Q8-a fields (NL)

Areas studied:

1. Horda Platform area
2. Grangemouth cluster
3. Teesside cluster
4. PORTHOS & ATHOS Projects

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IDENTIFYING CO_2 STORAGE CAPACITY & INFRASTRUCTURE FOR RE-USE

Storage readiness levels

ALIGN-CCUS reduces the uncertainty surrounding available storage site readiness.

Our new framework shows a CO_2 storage site's readiness level and the actions needed for it to become operational.

- Outlines steps, timescales & resources to achieve each stage
- Modelled on well-established Technology Readiness Levels framework
- Applicable to both saline formation & hydrocarbon field storage sites
- Based on experience of planning & operating North Sea CO_2 stores
- Compatible with and extends industry framework
- Applied framework to our study areas

	SRL NUMBER
SRL 1 - Initial identification of storage potential of a geological formation	SRL1
	SRL2
	SRL3
	SRL4
	SRL5
SRL 6 - 'Contingent storage resource'	SRL6
	SRL7
SRL 8 – design & construction	SRL8
SRL 9 - storage site 'on operation'	SRL9

Phased investment and investigation. Incremental increase in assurance of CO_2 containment, injection rate and storage capacity.

Legislative scenarios for infrastructure re-use

Uniquely, the project makes recommendations on fit-for-purpose legislation. If the infrastructure is needed in, say, five years, who is responsible for it financially and legally in the meantime?

- International law (Law of the Sea) requires removal of unused offshore installations; exact requirements may differ by country

ALIGN-CCUS has identified three scenarios:

- Award of storage licence at end of O&G production; production licence still in place
- Award of storage licence directly after production ceases; production licence lapses
- CO_2 storage to take place several years after production has ceased; production licence lapsed

Third scenario the most complex due to time gap:

- Assumed states will play crucial role as legally responsible for removal of installations
- Could appoint either interim entity or 'operator of last resort' to maintain infrastructure until needed. Requires more profound change to legal regime e.g. establishing which party (state or operator) responsible for infrastructure, including removal after CO_2 storage

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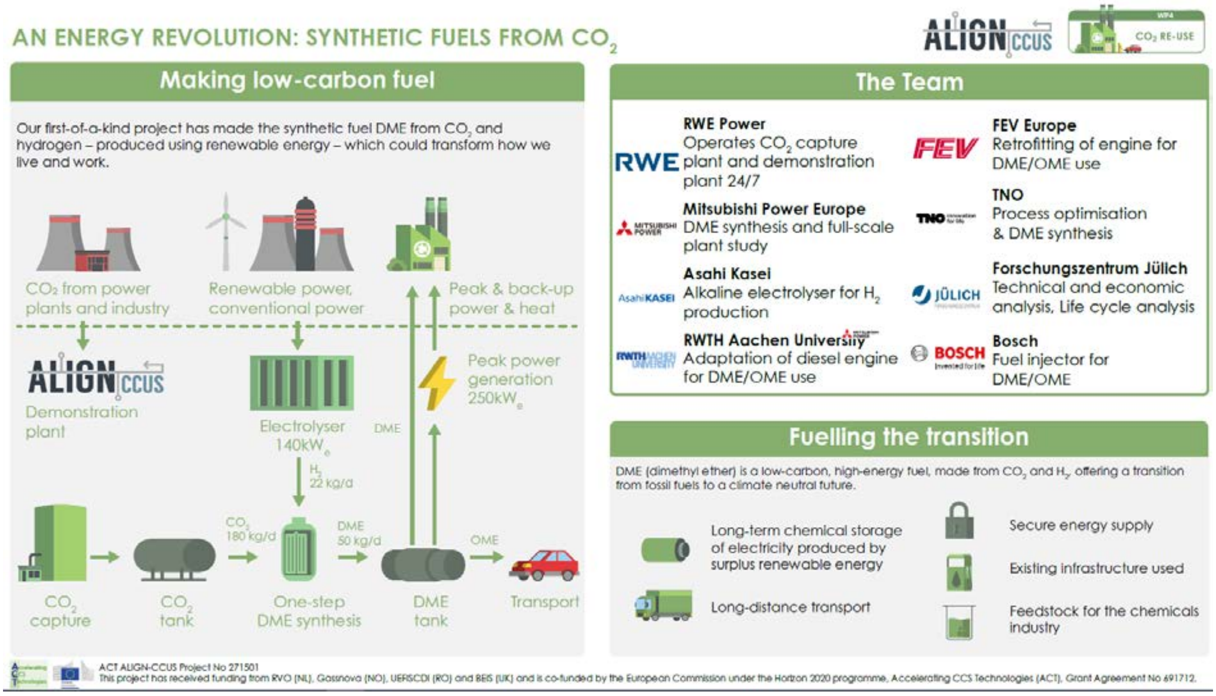
AN ENERGY REVOLUTION: SYNTHETIC FUELS FROM CO2
ALIGN CCUS
WP4 CO2 RE-USE
Making low-carbon fuel
Our first-of-a-kind project has made the synthetic fuel DME from CO2 and hydrogen – produced using renewable energy – which could transform how we live and work.
CO2 from power plants and industry
Renewable power, conventional power
Peak & back-up power & heat
ALIGN CCUS Demonstration plant
Electrolyser 140kWe
Peak power generation 250kWe
DME
H2 22 kg/d
CO2 180 kg/d
DME 50 kg/d
OME
CO2 capture
CO2 tank
One-step DME synthesis
DME tank
Transport
The Team
RWE Power
Operates CO2 capture plant and demonstration plant 24/7
Mitsubishi Power Europe
DME synthesis and full-scale plant study
Asahi Kasei
Alkaline electrolyser for H2 production
RWTH Aachen University
Adaptation of diesel engine for DME/OME use
FEV Europe
Retrofitting of engine for DME/OME use
TNO
Process optimisation & DME synthesis
Forschungszentrum Jülich
Technical and economic analysis, Life cycle analysis
Bosch
Fuel injector for DME/OME
Fuelling the transition
DME (dimethyl ether) is a low-carbon, high-energy fuel, made from CO2 and H2, offering a transition from fossil fuels to a climate neutral future.
Long-term chemical storage of electricity produced by surplus renewable energy
Long-distance transport
Secure energy supply
Existing infrastructure used
Feedstock for the chemicals industry
ACT ALIGN-CCUS Project No 271501
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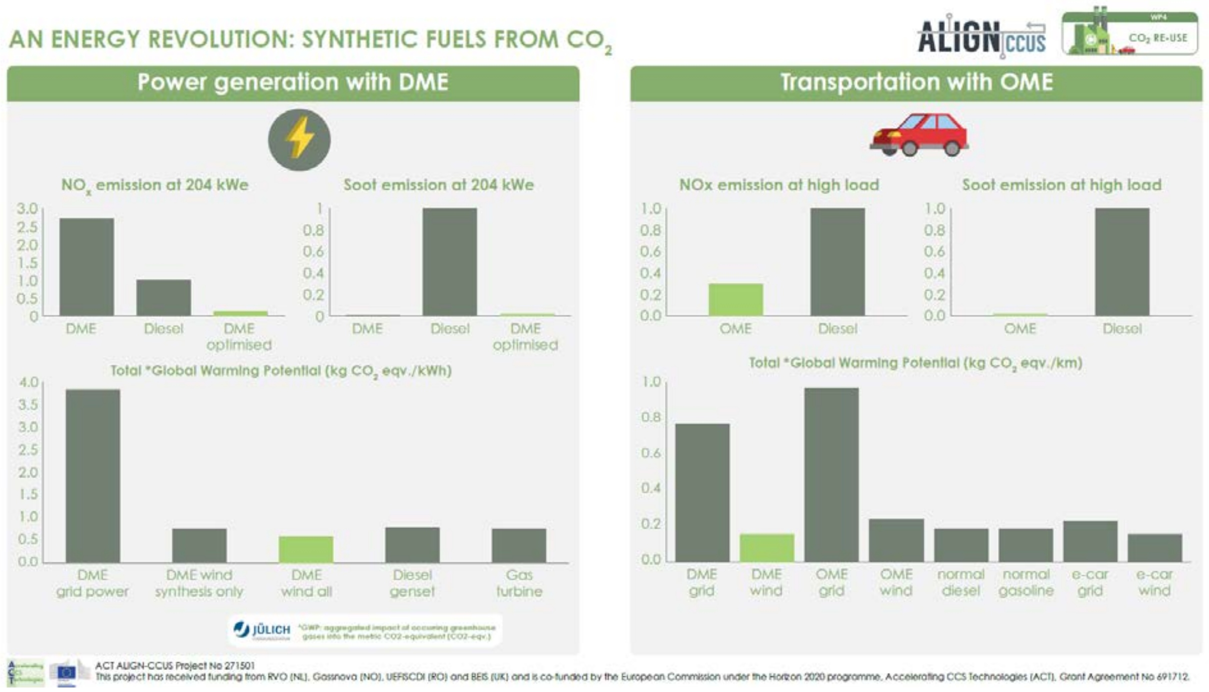
AN ENERGY REVOLUTION: SYNTHETIC FUELS FROM CO2
ALIGN CCUS
WP4 CO2 RE-USE
Power generation with DME
NOx emission at 204 kWe
DME
Diesel
DME optimised
Soot emission at 204 kWe
Total *Global Warming Potential (kg CO2 eqv./kWh)
DME grid power
DME wind synthesis only
DME wind all
Diesel genset
Gas turbine
JÜLICH
*GWP: aggregated impact of occuring greenhouse gases into the metric CO2-equivalent (CO2-eqv.)
Transportation with OME
NOx emission at high load
OME
Diesel
Soot emission at high load
Total *Global Warming Potential (kg CO2 eqv./km)
DME grid
DME wind
OME grid
OME wind
normal diesel
normal gasoline
e-car grid
e-car wind
ACT ALIGN-CCUS Project No 271501
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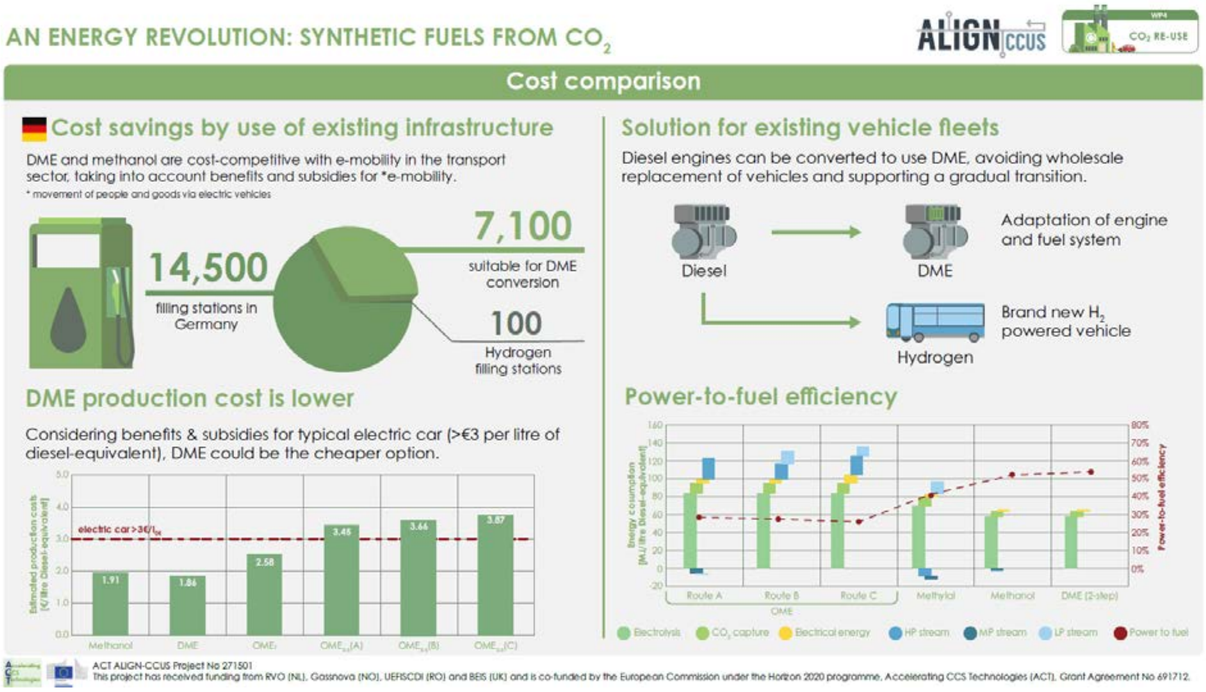
AN ENERGY REVOLUTION: SYNTHETIC FUELS FROM CO2
Cost comparison
Cost savings by use of existing infrastructure
DME and methanol are cost-competitive with e-mobility in the transport sector, taking into account benefits and subsidies for *e-mobility.
* movement of people and goods via electric vehicles
14,500
filling stations in Germany
7,100
suitable for DME conversion
100
Hydrogen filling stations
DME production cost is lower
Considering benefits & subsidies for typical electric car (>€3 per litre of diesel-equivalent), DME could be the cheaper option.
electric car >3€/l
1.91
1.86
2.58
3.45
3.66
3.87
Methanol
DME
Solution for existing vehicle fleets
Diesel engines can be converted to use DME, avoiding wholesale replacement of vehicles and supporting a gradual transition.
Diesel
DME
Adaptation of engine and fuel system
Hydrogen
Brand new H2 powered vehicle
Power-to-fuel efficiency
Route A
Route B
Route C
Methylal
Methanol
DME (2-step)
Electrolysis
Electrical energy
HP stream
MP stream
LP stream
Power to fuel
ACT ALIGN-CCUS Project No 271501
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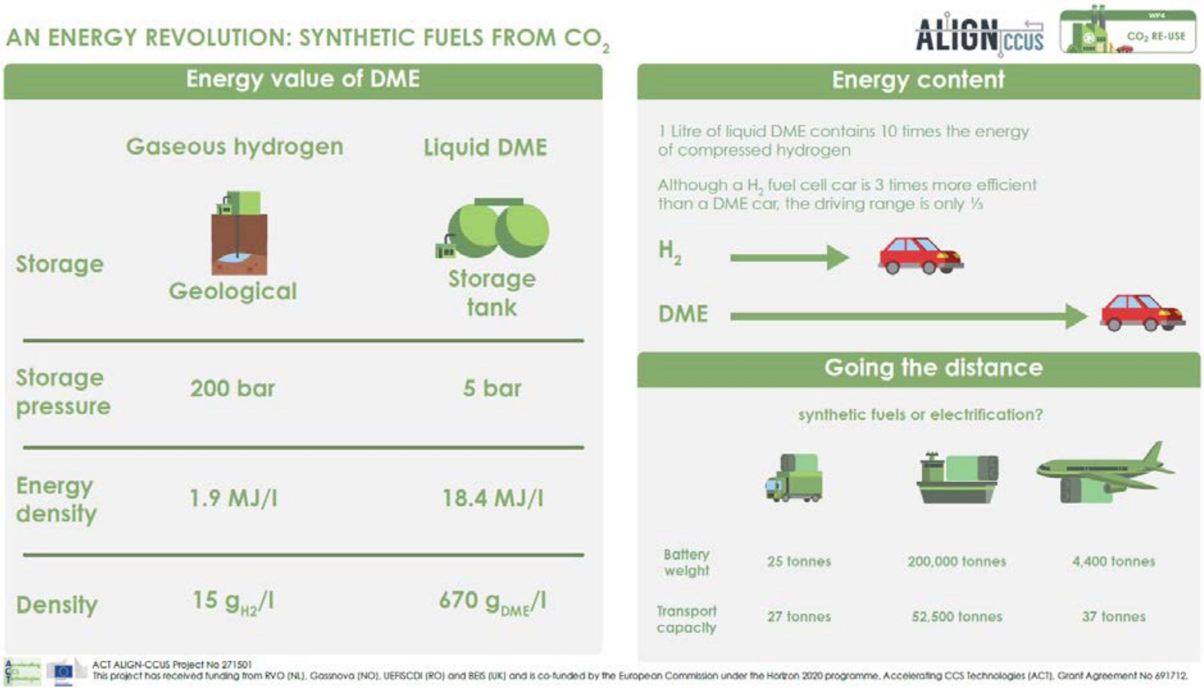
AN ENERGY REVOLUTION: SYNTHETIC FUELS FROM CO2
Energy value of DME
Gaseous hydrogen
Liquid DME
Storage
Geological
Storage tank
Storage pressure
200 bar
5 bar
Energy density
1.9 MJ/l
18.4 MJ/l
Density
15 gH2/l
670 gDME/l
Energy content
1 Litre of liquid DME contains 10 times the energy of compressed hydrogen
Although a H2 fuel cell car is 3 times more efficient than a DME car, the driving range is only ⅓
H2
DME
Going the distance
synthetic fuels or electrification?
Battery weight
25 tonnes
200,000 tonnes
4,400 tonnes
Transport capacity
27 tonnes
52,500 tonnes
37 tonnes
ACT ALIGN-CCUS Project No 271501
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DEVELOPING FULL-CHAIN CCUS FOR EUROPEAN INDUSTRY

Our research has identified the steps needed to develop full-chain CCUS in six industrial regions, helping sectors such as cement, chemicals and steel undergo a fundamental transformation in line with the EU's net-zero emissions goals.

- Examined specific infrastructure, technology, commercial & societal conditions needed.
- Created decision-making tool to evaluate prerequisites for cluster development.
- Developed cluster & hub approaches to reduce costs and commercial risk.

Industrial clusters

Grangemouth and Teesside, UK

- Plotted CO_2 capture rates identified & simulated storage capacity for CCS projects planned to 2055 and anticipated to 2100
- Recommended business & investment models for CCUS storage clusters, including barriers & risks, applied to both clusters
- Modelled costs and analysed optimal CO_2 transport & storage network development for business cases

Oltenia, Romania

- Conducted source & sink matching for Oltenia including evaluation of necessary infrastructure and transport & storage routes. Eight CCUS pathways identified
- Region's major CO_2 emissions totalled almost 15 Mt in 2018, nearly 38% of Romania's total industrial emissions
- Most viable option for CO_2 transportation is via pipeline between sites and then shipping to Black Sea storage via Danube

North Rhine-Westphalia, Germany

- Compiled database of nearly 120 CO_2 sources including sector, amounts, impurities and location
- Produced forecast of DME demand until 2050 & modelled optimised plant location, CO_2 source selection & network development
- Techno-economic optimisation process also investigated the impact of renewable energy input into the system and the impact of a centralised vs. decentralised DME facility

Grenland, Norway

- Conducted pre-feasibility study of an intermediate CO_2 storage site in Grenland including technology, engineering, operational, spatial & financial requirements
- Hub approach might reduce cost of CO_2 network due to larger volumes but requires cooperation between source companies on CO_2 impurities and logistics
- A shared pipeline to the reservoir could also become economically viable through the hub approach, enabling continuous injection instead of batched which is beneficial

Port of Rotterdam, Netherlands

- Significant potential for hydrogen use; 25% hydrogen can already be co-fired in existing natural gas turbines with limited modifications
- Current strategy, named H-Vision, estimates storage requirements for 288 Mt of CO_2; over 700 Mt capacity is estimated to be available on Dutch Continental Shelf
- Pathways include the use of CCS in the refining, petrochemical and power sectors

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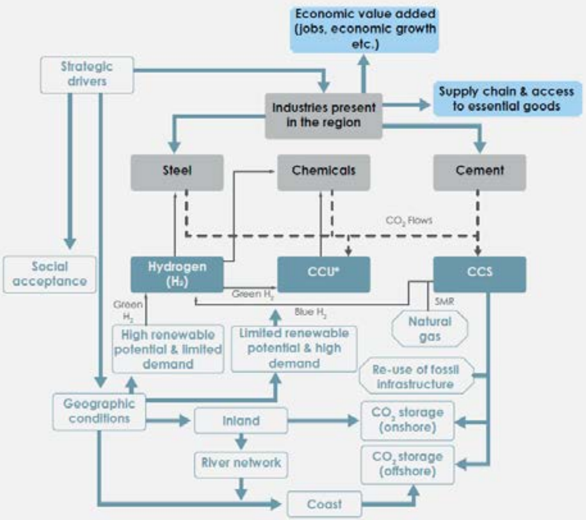
DEVELOPING FULL-CHAIN CCUS FOR EUROPEAN INDUSTRY

Project factors & conditions

ALIGN-CCUS has developed a **decision-making tool** to help evaluate the factors & conditions needed for successful CCUS projects & industrial decarbonisation.

Identifying & implementing the best climate path for clusters

- The makeup and location of industry clusters and their access to resoucres will dictate the role different technologies will play.
- The economic value of industry in the region is the main strategic driver and needs to be well understood.
- Interconnections with other regions, technologies and sectors of the economy needs to be established.



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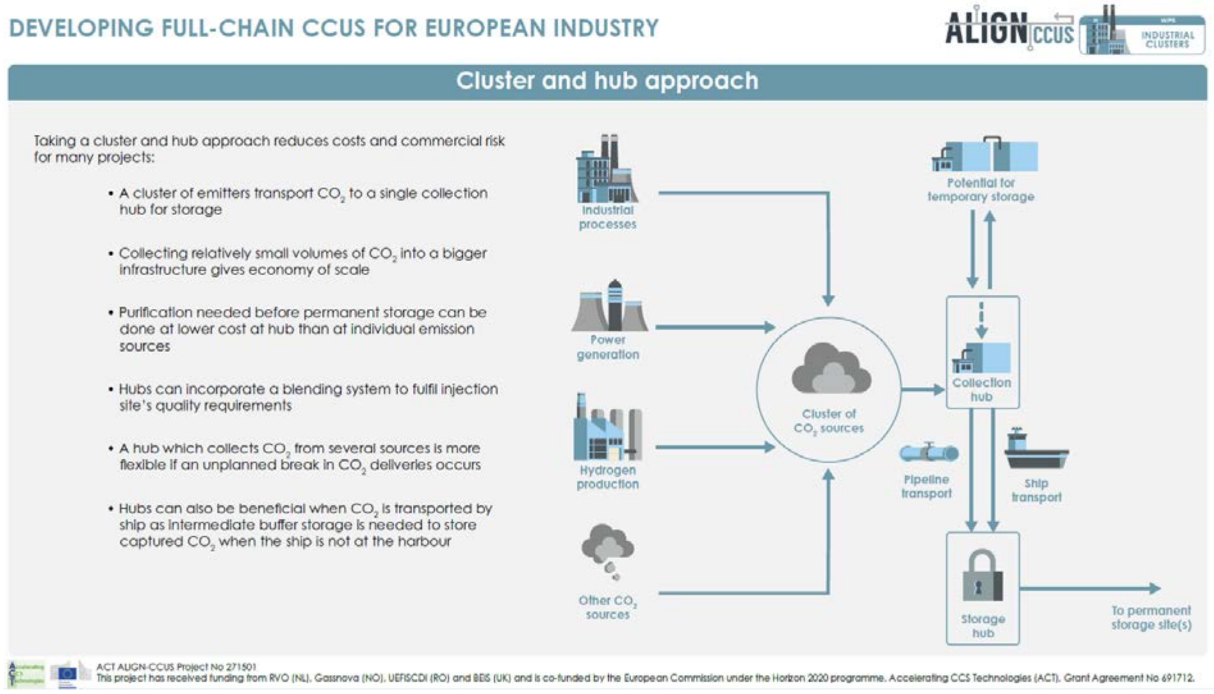
DEVELOPING FULL-CHAIN CCUS FOR EUROPEAN INDUSTRY
ALIGN CCUS
INDUSTRIAL CLUSTERS
Cluster and hub approach
Taking a cluster and hub approach reduces costs and commercial risk for many projects:
• A cluster of emitters transport CO_2 to a single collection hub for storage
• Collecting relatively small volumes of CO_2 into a bigger infrastructure gives economy of scale
• Purification needed before permanent storage can be done at lower cost at hub than at individual emission sources
• Hubs can incorporate a blending system to fulfil injection site's quality requirements
• A hub which collects CO_2 from several sources is more flexible if an unplanned break in CO_2 deliveries occurs
• Hubs can also be beneficial when CO_2 is transported by ship as intermediate buffer storage is needed to store captured CO_2 when the ship is not at the harbour
Industrial processes
Power generation
Hydrogen production
Other CO_2 sources
Cluster of CO_2 sources
Potential for temporary storage
Collection hub
Pipeline transport
Ship transport
Storage hub
To permanent storage site(s)
ACT ALIGN-CCUS Project No 271501
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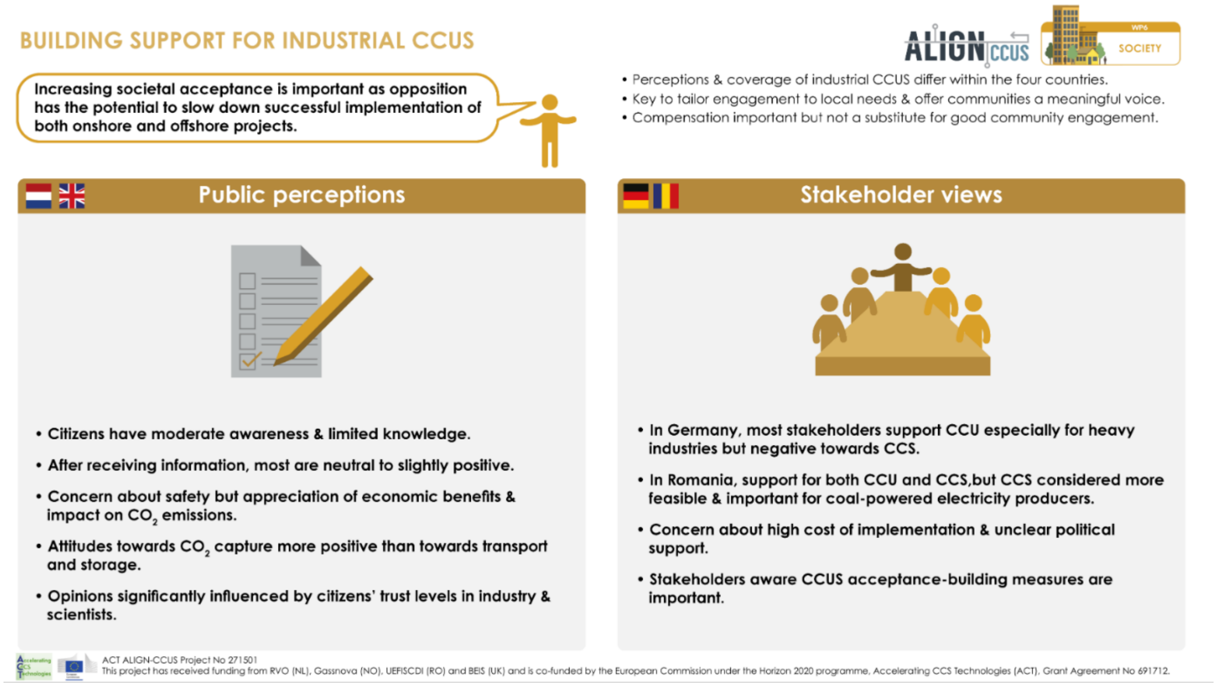
BUILDING SUPPORT FOR INDUSTRIAL CCUS
ALIGN CCUS
SOCIETY
Increasing societal acceptance is important as opposition has the potential to slow down successful implementation of both onshore and offshore projects.
• Perceptions & coverage of industrial CCUS differ within the four countries.
• Key to tailor engagement to local needs & offer communities a meaningful voice.
• Compensation important but not a substitute for good community engagement.
Public perceptions
• Citizens have moderate awareness & limited knowledge.
• After receiving information, most are neutral to slightly positive.
• Concern about safety but appreciation of economic benefits & impact on CO_2 emissions.
• Attitudes towards CO_2 capture more positive than towards transport and storage.
• Opinions significantly influenced by citizens' trust levels in industry & scientists.
Stakeholder views
• In Germany, most stakeholders support CCU especially for heavy industries but negative towards CCS.
• In Romania, support for both CCU and CCS,but CCS considered more feasible & important for coal-powered electricity producers.
• Concern about high cost of implementation & unclear political support.
• Stakeholders aware CCUS acceptance-building measures are important.
ACT ALIGN-CCUS Project No 271501
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BUILDING SUPPORT FOR INDUSTRIAL CCUS
ALIGN CCUS
WP6
SOCIETY
Testing & creating core messages
• Coverage levels & type of discourse differ in media & website coverage in the four countries. Netherlands, Romania & UK: focus is on capture & storage. Germany: stronger focus on transport & on perceived safety risks than elsewhere.
• Similar arguments used for/against CCS. Proponents say sustainable & proven technology, opponents say not sustainable and unproven. Makes it difficult for the public to form an opinion on already complex subject.
• CO_2 utilisation attracts little coverage but providing information about it may help increase public interest & support for CCUS.
Community engagement & compensation
• Community compensation not a substitute for good engagement.
• Engagement & compensation recommended for both onshore & offshore developments.
• Dealing with internal & government stakeholders important but community engagement managers indicate can be challenging.
• Key to tailor engagement to local needs & offer communities a meaningful voice.
• Institutionalised but flexible approach to compensation may prevent perceptions of bribery & promote project acceptance.
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